Ref. Ares(2026)8297699 - 31/08/2026

Re-Livestock
RESILIENT FARMING SYSTEMS

Deliverable D5

Novel feeds to lower the carbon footprint of pig and beef production



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Re-Livestock
RESILIENT FARMING SYSTEMS

Deliverable D5
Novel feeds to lower the carbon footprint of pig and beef production

Project Number:	101059609
Project:	Re-Livestock - Facilitating Innovations for Resilient Livestock Farming Systems
Duration:	60 months
Start date of Project:	1 September 2022
Project management:	CSIC - AGENCIA ESTATAL CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS
Deliverable:	**D5 (D2.2)**
Due date of deliverable:	**31 August 2026**
Actual submission date:	**31 August 2026**
Work package:	**WP2**
Leader:	**SRUC**
Person in charge:	**John Newbold and Rosa Nieto**
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Contributors:	**Pedro Herráiz, Mar González**
Communication level:	**PU**
Version:	**1**

Executive Summary

Feed production is a major contributor to the environmental footprint of pig and beef production, while protein supply is particularly important because of its associated land, energy, water and greenhouse-gas emissions. The Re-Livestock research activities therefore evaluated a range of feeding strategies aimed at reducing dependence on imported soybean products, improving nutrient-use efficiency and increasing the use of locally available or circular feed resources.

In pig production, three complementary approaches were investigated: (i) replacement of soybean meal with locally produced legumes and alternative protein sources; (ii) incorporation of agri-food industry by-products; and (iii) reduction of dietary crude protein through targeted amino-acid supplementation. Across several experiments and pig genotypes, locally produced peas, chickpeas, lentils, faba beans and narrow-leafed lupine successfully replaced part or all of soybean protein without compromising overall growth performance. Peas generally showed the most consistent nutritional response, while faba beans and lupine also maintained performance and, in some cases, improved feed efficiency and carcass characteristics. Importantly, the legume-based diets did not adversely affect intestinal health, and some studies indicated improved nitrogen-use efficiency or reduced indicators of intestinal inflammation.

The use of dried berry pomaces demonstrated the potential of food-industry by-products to provide additional nutritional and environmental benefits. Inclusion of blackcurrant and chokeberry pomaces did not impair overall growth or nutrient digestibility and was associated with improved nitrogen retention in some treatments and potential reductions in methane and ammonia emissions.

The low-protein diet studies demonstrated that reducing dietary crude protein can substantially reduce nitrogen excretion and ammonia emissions while maintaining production efficiency and improving selected pork-quality characteristics. However, the benefits depend critically on supplying essential amino acids at adequate levels. Meeting, rather than exceeding, amino-acid requirements was sufficient to improve feed efficiency and nitrogen utilisation, indicating that precision protein nutrition is central to the successful implementation of low-protein diets. Further work on circular protein ingredients is ongoing.

Insect protein provided another promising alternative, with complete replacement of soybean protein by *Hermetia illucens* or *Tenebrio molitor* meal maintaining growth, nutrient utilisation and intestinal health under the conditions tested. *Hermetia illucens* showed particularly favourable productive responses.

In beef production, soybean meal-free diets based on combinations of locally produced cereals, sugar beet pulp, DDGS and, in one treatment, rumen-protected lysine and methionine (together with reducing total crude protein content of the diet) were evaluated under commercial feedlot conditions in Spain. The approach demonstrates the feasibility of designing diets with substantially reduced reliance on soybean-derived ingredients while using complementary local and alternative feed resources. The associated PLF and LCA approaches provide a framework for evaluating both productive performance and environmental consequences at farm level.

The UK study further examined the environmental and economic trade-offs associated with the use of brewers' spent grains as animal feed compared with anaerobic digestion. Together, these studies demonstrate that feed diversification, circular use of agri-food co-products, local protein production and precision formulation can contribute to more resilient and potentially lower-carbon livestock systems. However, environmental benefits cannot be inferred solely from ingredient substitution: they depend on feed composition, inclusion level, nutrient utilisation, ingredient origin, processing and the resulting animal performance. Integrated assessment of nutritional, productive, economic and environmental performance is therefore essential when identifying the most sustainable feeding strategies for European pig and beef production.

1. Novel feeds to lower the carbon footprint of pig production

Feed production represents an important component of the environmental footprint of pig production, particularly in intensive European systems that rely heavily on concentrated feeds. Protein sources are especially relevant because their production requires substantial land, water and energy resources. Soybean meal is currently the main protein source used in pig diets due to its high nutritional value and balanced amino acid profile. However, European pig production is highly dependent on imported soybean meal, raising concerns related to environmental sustainability, increasing prices, competition for land between feed and food production, and dependence on third-country imports. Consequently, reducing the use of imported soybean meal through alternative protein sources represents a promising strategy to decrease greenhouse gas emissions and improve the resilience of European pig production systems.

i) **Locally produced grain legumes**, including lupins, faba beans, peas, chickpeas, and lentils, represent particularly promising alternatives to soybean meal due to their relatively high protein content and their potential to partially or, in some cases, fully replace soybean meal in pig diets. Increasing their use could support more circular and lower-emission feeding systems, although differences in nutrient digestibility, amino acid profiles, and the presence of anti-nutritional factors must be carefully considered during diet formulation.
ii) Other **alternative protein sources**, such as **insect meals**, may also contribute to reducing reliance on soybean-derived protein.
iii) An additional strategy to decrease European dependence on imported soybean meal is to reduce the dietary crude protein content through appropriate amino acid supplementation. However, the feasibility of this approach should be further evaluated under different sanitary conditions to ensure that reductions in dietary protein do not compromise pig performance, health, or welfare.
iv) The valorisation of **agri-food industry by-products**, such as fruit pomaces, offers an additional opportunity to enhance the sustainability of pig feeding by incorporating nutrient- and bioactive-rich materials into animal diets while simultaneously reducing waste. Certain by-products may also beneficially modulate intestinal microbial fermentation and potentially contribute to reducing greenhouse gas emissions.

The experimental work with pigs designed and conducted within the Re-Livestock project evaluated the feasibility, nutritional implications, and environmental benefits of these nutritional strategies. Overall, increasing the use of locally available protein crops, alternative protein sources, and agri-food industry by-products, together with strategies aimed at reducing dietary protein levels, could substantially reduce European reliance on imported soybean meal and contribute to lowering the carbon footprint of pig production without compromising animal performance or health. Details of these nutritional strategies and outcomes are briefly described in the following sections.

1.1 Local legumes as substitutes of soyabean meal

1.1.1 Studies at Poznań University of Life Sciences (PULS)

Sustainable livestock production requires the implementation of feeding strategies that both reduce environmental impact and enhance farm resilience to economic and climatic variability. In this context, the cultivation and on-farm utilization of narrow-leafed lupine (*Lupinus* spp.) and faba bean *(Vicia faba* L.) seeds represent a promising approach to developing circular, low-emission feeding systems. Such strategies are particularly well suited to indigenous pig breeds adapted to low-input production conditions.

Objectives

Building on existing knowledge of the nutritional value of these legumes and their role in closed-loop agricultural systems, the study aimed to evaluate the effectiveness of diets incorporating narrow-leafed lupine or faba bean seeds in feeding a Polish native pig breed (Puławska). Additionally, the study assessed their effects on fattening performance and slaughter characteristics, providing a basis for determining the potential of these locally produced protein sources within sustainable livestock production models.

Methods

The experiment was conducted on a commercial farm using a total of 75 pigs (25 per group; 15 females and 10 males), with an initial body weight of approximately 36 kg. Animals were housed on a slatted floor and randomly allocated to three dietary treatments. The control group (CON) was fed a diet based on soybean meal (SBM), whereas in the experimental groups SBM was replaced with faba bean (FB) or narrow-leafed lupine (NL) seeds. Animals were maintained under uniform fattening conditions with ad libitum access to feed and water. Body weight gain (BWG) and group feed intake (FI) were recorded, and the feed conversion ratio (FCR) was calculated for the entire experimental period (117 days). After reaching approximately 50 kg body weight, eight animals from each group (4 females and 4 males) were transferred to metabolic cages for a two-day period to determine apparent total tract digestibility (ATTD) coefficients of dry matter (DM), crude protein (CP), phosphorus (P), and gross energy (GE), as well as nitrogen balance, using the total collection method. Feed intake, along with faeces and urine output, was measured, and representative samples were collected for analysis. At the end of the trial, eight pigs per group (4 females and 4 males) were slaughtered. Post-mortem carcass measurements were performed, and biological material, including fat and meat samples, was collected for analysis. Statistical analyses were conducted using one-way analysis of variance (ANOVA), followed by Duncan's multiple range test, with significance declared at $P \leq 0.05$.

Results and Discussion

During the grower phase, pigs fed the NL diet exhibited lower total body weight gain compared to the CON and FB groups ($P < 0.05$), while no significant differences in FCR were observed at this stage (Table 1). In the finisher phase, growth performance parameters, including final body weight as well as total and daily weight gain, were not affected by dietary treatment. However, FCR was significantly

improved in the NL group compared to the FB group ($P < 0.05$), with the CON group showing intermediate values. Over the entire experimental period, no significant differences were found in total or daily BWG among the groups (Table 1).

Table 1. Effect of feeding faba or lupine beans on performance indices

Period	***Group***	*Control – SBM*	*Faba bean*	*Lupine*	*P-value*
	Initial BW (kg)	36.5	37.7	37.2	NS
Grower	BW (kg)	77.8	79.7	74.8	NS
	Gain (kg)	41.2[a]	42.0[a]	37.6[b]	P<0.05
	Daily gain (kg)	0.70[a]	0.71[a]	0.64[b]	P<0.05
	FI/pig (kg)	136.0	140.0	115.0	NA
	FCR (kg/kg)	3.38	3.42	3.14	NS
Finisher	BW (kg)	123.0	121.5	118.5	NS
	Gain (kg)	45.3	41.9	43.7	NS
	Daily gain (kg)	0.78	0.72	0.75	NS
	FI/pig (kg)	174.0	166.0	150.0	NA
	FCR (kg/kg)	3.91[ab]	4.19[a]	3.49[b]	P<0.05
Total	Gain (kg)	86.5	83.9	81.3	NS
	Daily gain (kg)	0.74	0.72	0.70	NS
	FI/pig (kg)	310.0	306.0	265.0	NA
	FCR (kg/kg)	3.62[a]	3.70[a]	3.31[b]	P<0.05

Pigs fed the NL diet demonstrated significantly better feed efficiency, as indicated by a lower FCR compared to both the CON and FB groups ($P < 0.05$). Furthermore, carcasses of pigs from the NL group exhibited approximately 5.75 mm lower fat thickness measured at the gluteal muscle (KIII) cross-section compared to CON pigs fed SBM. In contrast, pigs from the FB group were characterized by longer carcasses, higher meatiness, reduced backfat thickness, and lower cooking losses compared to the CON group (Table 2; $P < 0.05$). No significant differences were observed among groups in the ATTD of DM, CP, P, and GE. Similarly, serum concentrations of ALT, ALP, total protein, cholesterol, and creatinine were not affected by dietary treatment. However, selected biochemical parameters were significantly influenced (Table 3). Pigs fed the NL diet exhibited higher AST activity ($P < 0.05$), whereas total bilirubin and glucose concentrations were elevated in the FB group compared to the other treatments. In contrast, urea levels were higher in pigs receiving the NL diet. Additionally, triglyceride concentrations were increased in both the FB and NL groups relative to the control.

Table 2. Effect of feeding faba or lupine beans on carcass characteristics

Groups	*Control – SBM*	*Faba bean*	*Lupine*	*P-value*
Carcass weight (kg)	199.8	95.8	95.5	NS
Meatiness (%)	56.02[b]	58.69[a]	57.27 [ab]	P<0.0S
Carcass length (cm)	84.62[b]	87.38 [a]	86.75 [ab]	P<0.05
Carcass width (cm)	39.25	40.63	39.25	NS
Gluteal muscle thickness (mm)	73.25	78.00	74.38	NS
Backfat (mm)	26.50[a]	21.75[c]	23.12[b]	P<0.05
Shoulder backfat (mm)	44.38	42.50	42.50	NS
KIII (mm)	26.62[a]	22.25 [ab]	20.87[b]	P<0.05
KII (mm)	19.63	17.38	16.75	NS
KI (mm)	28.75	27.13	25.13	NS

Table 3. Effect of feeding faba or lupine beans on blood serum parameters

Blood serum parameters	*Unit*	*Control – SBM*	*Faba bean*	*Lupine*	*P-value*
ALT	U/L	60.02	64.57	69.32	NS
AP	U/L	121.4	102.6	107.9	NS
AST	U/L	54.74[b]	52.36[b]	69.70[a]	P<0.05
Total protein	g/L	74.50	78.95	76.67	NS
Total bilirubin	µmol/L	2.65[b]	3.57[a]	2.57[b]	P<0.05
Cholesterol	mmol/L	2.433	2.476	2.546	NS
Glucose	mmol/L	5.29[b]	6.93[a]	5.17[b]	P<0.05
Creatinine	µmol/L	139.67	147.9	156.34	NS
Urea	mmol/L	4.87[b]	4.30[b]	5.35[a]	P<0.05
Triglycerides	mmol/L	0.41[b]	0.58[a]	0.57[a]	P<0.05

Conclusions

Substituting soybean meal with faba beans and narrow-leafed lupine seeds did not compromise growth performance and improved feed conversion efficiency. Additionally, their inclusion positively influenced carcass traits by reducing fat deposition and cooking losses, providing benefits for both producers and consumers. These findings highlight the potential and the importance of selecting appropriate legume seed types in livestock diets as part of strategies for implementing closed-loop feeding systems.

Dissemination:

(1) EAAP-ASAS Conference on Livestock farming and the environment: emissions and solutions. Book of Abstracts No. 40 (2026) Angra do Heroísmo – Terceira Island (Azores), Portugal, 19-21 April, 2026 (Poster 16)
Potential environmental and production benefits of integrating farm-grown lupin and faba bean seeds into closed-loop feeding systems for native pig breeds

(2) 5th International Legume Society Conference ♦ 8 – 12 June 2026 ♦ Dubrovnik, Croatia Potential benefits of using lupin and faba bean seeds in the feeding of native pig breeds on meat quality and production, and environmental conditions (p. 128)..

1.1.2. Studies at Animal Data Analytics (ADA, Spain)

Soybean meal is the main protein source used in pig nutrition due to its high nutritional value and balanced amino acid profile. However, the increasing dependence on imported soybean has raised concerns regarding production costs, supply security and environmental sustainability. Consequently, there is growing interest in identifying locally produced protein sources that can partially or totally replace soybean meal without compromising animal performance or health.
Grain legumes such as peas, chickpeas and lentils are widely cultivated in Mediterranean regions and represent promising alternatives because of their high protein content and local availability. Nevertheless, differences in nutrient digestibility and the presence of anti-nutritional factors may influence their nutritional value in pig diets. Therefore, their practical use under commercial production conditions requires further evaluation.

Objectives

The objective of this study was to evaluate the feasibility of replacing soybean meal with locally produced peas, chickpeas and lentils in growing pig diets under commercial conditions. Specifically, the study assessed the effects of partial (50%) or complete (100%) soybean protein replacement on growth performance, health status, apparent faecal digestibility, intestinal inflammatory biomarkers, caecal fermentation profile, and intestinal histomorphology.

Methods

A total of 504 commercial crossbred pigs (Pietrain × DNA; initial BW 18.4 ± 1.3 kg) were included in the study. Animals were distributed into two consecutive batches (summer and thermoneutral conditions), with 252 pigs per batch. The experiment followed a randomized complete block design including seven dietary treatments, 12 replicate pens per treatment (6 per batch) and 6 pigs per pen. Experimental diets were fed during the 28-day growing period, after which pigs received a common commercial finishing diet. Feed and water were provided *ad libitum*.

Seven experimental diets were formulated (Table 2). The control diet contained soybean meal as the main protein source, whereas the remaining diets included peas, chickpeas or lentils replacing soybean protein either partially (50%) or totally (100%). All diets were formulated to be isoenergetic and isonitrogenous, meeting or exceeding FEDNA (1) nutrient recommendations for growing pigs, and did not contain antibiotics or growth promoters.

Table 4. Scheme of experimental dietary treatments.

Treatment	Main protein source	Soybean protein replacement	Local legume inclusion (g/kg feed)
T1	Soybean meal	0%	0
T2	Pea + soybean meal	50%	195
T3	Pea	100%	470
T4	Chickpea + soybean meal	50%	201
T5	Chickpea	100%	490
T6	Lentil + soybean meal	50%	162
T7	Lentil	100%	365

Growth performance was evaluated through body weight, ADG, ADFI, FCR and body weight homogeneity. Health status was monitored throughout the trial by recording mortality, culling, diarrhoea incidence and faecal score. Faecal samples were collected on days 0, 14 and 28 to determine myeloperoxidase (MPO) activity and calprotectin concentration as biomarkers of intestinal inflammation. Apparent faecal digestibility of dry matter, organic matter and crude protein was determined during the last week of the growing period using acid-insoluble ash as an inert marker.
At the end of each batch, pigs were slaughtered for collection of colon digesta to quantify volatile fatty acids (VFA), and samples of ileum and jejunum were obtained for histomorphological evaluation (villus height and crypt depth).

Results and Discussion

Replacing soybean meal with locally produced legumes maintained or improved growth performance throughout the growing period. Although the response varied between production batches, peas consistently produced the most favourable productive results, while chickpea and lentil supported intermediate performance without negatively affecting animal growth (Table 2).

Table 5. Main effects of dietary treatments on productive performance.

Parameter	Main significant findings	Biological relevance
Final body weight	In the summer batch, pigs fed Pea100 reached the highest final BW (29.4 kg) compared with the soybean control (26.1 kg; $P<0.05$). Contrast analyses showed that all legume diets resulted in higher final BW than the control. Under thermoneutral conditions, pea diets again showed the best productive response.	Pea was the most effective alternative to soybean meal, whereas chickpea and lentil maintained satisfactory growth.
Average daily gain	Pea100 showed the highest ADG ($P<0.05$), while all legume diets achieved greater ADG than the soybean control in contrast analyses. No differences in ADFI or FCR were detected.	Improved growth was achieved without increasing feed intake or reducing feed efficiency.
Feed intake and efficiency	ADFI, FCR and body weight homogeneity were not affected by dietary treatment.	Soybean replacement did not compromise feeding efficiency or animal uniformity.

Health status remained stable throughout the study regardless of dietary treatment. Mortality, diarrhoea incidence and faecal consistency were not influenced by soybean replacement. Similarly, faecal MPO concentrations were unaffected, whereas calprotectin showed only limited treatment effects, with higher concentrations in chickpea-fed pigs only in one of the trials (Table 3).

Table 6. Main effects on gut health and nutrient digestibility

Parameter	Main significant findings	Biological relevance
Health indicators	No differences in mortality, diarrhoea or faecal score among treatments. MPO concentrations remained unchanged throughout the study.	Complete soybean replacement did not impair animal health or intestinal inflammatory status.
Calprotectin	Higher faecal calprotectin concentrations were detected in chickpea-fed pigs during the second trial (thermoneutral batch, P<0.05).	The response was treatment-specific and was not associated with impaired health or performance.
Apparent digestibility	Pea diets showed the highest digestibility coefficients. In the thermoneutral batch, Pea100 reached 89.60% DM, 90.74% OM and 85.79% CP digestibility, whereas Chickpea50 showed the lowest values (86.16%, 87.88% and 80.23%, respectively; P<0.001).	The greater nutrient utilisation observed for peas probably contributed to their superior productive performance.

Dietary treatments induced only moderate modifications in hindgut fermentation and intestinal morphology, indicating that replacement of soybean meal had limited effects on gastrointestinal function (Table 4).

Table 7. Main effects on intestinal physiology.

Parameter	Main significant findings	Biological relevance
Volatile fatty acids	Chickpea diets increased straight-chain VFA concentrations (110.3–110.6 mmol/L) compared with the control (80.0 mmol/L; P=0.0479), while reducing the branched-chain ratio. Lentil diets also reduced the branched-chain ratio.	Local legumes modified microbial fermentation, although the changes were modest and treatment-specific.
Ileal morphology	Under thermoneutral conditions, Pea100 showed the greatest villus height and mucosal development, whereas during the summer batch the control exhibited longer villi and chickpea increased crypt depth.	Pea promoted the most favourable intestinal morphology under optimal environmental conditions.
Jejunal morphology	Significant treatment differences were detected, but no consistent response across protein sources was observed. Chickpea100 showed the highest villus height and villus:crypt ratio in the second production cycle.	Jejunal adaptations were variable and did not appear to explain the differences in productive performance.

Conclusions

- Locally produced peas, chickpeas and lentils successfully replaced soybean meal without compromising the health or performance of growing pigs.
- Peas provided the most consistent productive response, showing superior growth performance, nutrient digestibility and intestinal development.
- Chickpeas and lentils represented suitable alternative protein sources, although their nutritional value was slightly more variable than that of peas.
- Soybean replacement produced only minor changes in intestinal physiology and did not induce relevant intestinal inflammation.

These results support the use of locally produced legumes as sustainable protein sources for pig production, contributing to a reduction in the dependence on imported soybean meal.

References

1. De Blas, C.; Gasa, J.; Mateos, G.G.; Madrid, U.P.; Barcelona, U.A. Necesidades Nutricionales Para Ganado Porcino Normas FEDNA,2nd ed.; Fundación Española para el Desarrollo de la Nutrición Animal: Madrid, Spain, 2013.

Dissemination:

(1) Book of Abstracts of the 75th Annual Meeting of the European Federation of Animal Science, pg. 832. Florence, Italy, 1-5 September, 2024. Oral presentation.
M. Rodríguez; I. Fernández-Fígares; R. Nieto; J. Morales. Evaluation of the soybean replacement as protein source with Mediterranean legumes in the performance of growing pigs.

(2) Book of Abstracts of the 75th Annual Meeting of the European Federation of Animal Science, pg. 1045. Florence, Italy, 1-5 September, 2024. Oral presentation.
I. Fernández-Fígares; M. Rodríguez; R. Nieto; J. Morales. Effect of replacement of soybean by Mediterranean legumes on intestinal health of growing pigs

(3) Iberian Congress on Legumes. Bases for Agricultural and Food Sustainability. León, Spain, 13-15 November, 2024. Book of Abstracts, communication M3.2-O-01 pg. 109-110. Oral presentation.
M. Rodríguez, J. Morales, R. Nieto, I. Fernández-Fígares. (*Evaluación del reemplazo de la soja por legumbres autóctonas en cerdos en crecimiento en condiciones de estrés por calor*). Evaluation of soybean replacement by native legumes in growing pigs under heat stress.

1.1.3. Studies at Spanish National Research Council (EEZ-CSIC)

Global climate change presents an urgent challenge, driving the need to mitigate greenhouse gas (GHG) emissions across all sectors. Swine production contributes accounting for approximately 13% of livestock-related emissions (1). The primary gases involved are methane (CH_4) and nitrous oxide (N_2O) from manure storage and microbial soil processes, respectively, together with carbon dioxide (CO_2) (2) from direct farm energy use and extensive transport logistics across the meat production chain (3).
Protein is one of the most expensive and environmentally limiting components in feed formulation, and its production heavily impacts land use, water, and energy resources (2). European swine production relies on concentrated feeds, particularly imported soybean meals (4). In recent years, alternatives to soy are being sought due to the increases in its prices, ethical issues, environmental impact, and competition for land use for feed and food, in addition to reducing the sector's dependence in Europe on third countries (4). Local legumes species currently represent a valuable alternative with the potential to partially or totally replace soy, along with insect meals, microalgae, or macroalgae (5). As European intensive swine production systems rely heavily on concentrated feeds, the substitution of soy with alternative protein sources is considered a good option to reduce GHG emissions from swine production (6).

Objectives

The studies aimed at assessing the effects of replacing 50% of soybean protein with protein from locally grown peas, chickpeas and lentils (the last two, discarded from human consumption) on productive and metabolic parameters of growing pigs. Two trials were designed to evaluate the effects of soybean substitution both in cosmopolitan and native (Iberian) pigs.

Methods

All diets were isoenergetic and isoproteic, with similar digestible lysine/essential amino acid ratios and nutritionally balanced for growing pigs.

First trial: (Duroc × Pietrain) × (Landrace × Large-White) pigs were used for evaluating 50% soybean protein substitution in growth performance, total tract apparent digestibility (TTAD) of nutrients, N balance, biochemical parameters and intestinal inflammation.

32 (Duroc × Pietrain) × (Landrace × Large-White) pigs were randomly assigned to one of the following treatments: control, or local legume-fed groups (50% of soybean protein replaced by peas, chickpeas, or lentils, respectively). Initial body weight (BW) was 14 ± 0.3 and final BW was 66 ± 0.9. After 3 weeks, TTAD of nutrients and nitrogen balance experiments were carried out in 6 animals per treatment. Individual feed consumption was recorded and feces and urine individually quantified and collected over 4 days to obtain a representative sample. 10 weeks after the beginning of the trial, the animals were slaughtered and blood samples taken to analyze biochemical parameters. Faeces samples from the colon were taken to determine markers of intestinal inflammation

Second trial: Iberian pigs were used for evaluating substitution of soybean meals with locally grown legumes in terms of growth performance, total tract apparent digestibility (TTAD) of nutrients, N balance, biochemical parameters and intestinal inflammation.

32 Iberian pigs were randomly assigned to one of the following treatments: control, or local legume-fed groups (50% of soybean protein replaced by peas, chickpeas, or lentils, respectively). Initial BW was 33 ± 1.3 kg and final BW 74 ± 2.5 kg. After 3 weeks, TTAD of nutrients and nitrogen balance experiments were carried out in 6 animals per treatment. Individual feed consumption was recorded and feces and urine individually quantified and collected over 4 days to obtain a representative sample. 10 weeks after the beginning of the trial, the animals were slaughtered and blood samples taken to analyze biochemical parameters. Faeces samples from the colon were taken to determine markers of intestinal inflammation.

Analysis of variance was performed to study the effect of treatments on the evaluated parameters using the STATGRAPHICS Centurion XVI statistical package version 16.1.18 (StatPoint Technologies Inc., Warrenton, VA). Pig was the experimental unit and significance level was set at 0.05.

Results and Discussion

First trial: (Duroc × Pietrain) × (Landrace × Large-White).
The substitution of 50% soybean protein with local peas, chickpeas, or lentils did not negatively affect productive parameters (Table 5). Final BW, average daily gain (ADG) and the gain/feed ratio remained statistically comparable to the control group. This suggest that alternative local legume protein sources can successfully sustain conventional pig growth when diets are properly balanced on an isoenergetic and isoproteic basis.

Table 8: Effect of dietary treatments on productive parameters of cosmopolitan pigs

	Dietary treatments				SEM	*P*-value
	Control	Peas	Chickpeas	Lentils		
Initial BW, kg	13.7	13.9	13.9	14.2	0.64	0.98
Final BW, kg	68.7	64.1	67.1	66.8	1.89	0.40
ADG, g	812	743	788	779	31.0	0.48
Average intake, g/d	1499	1383	1479	1446	61.6	0.57
Gain/feed	0.545	0.527	0.533	0.539	0.008	0.51

Regarding TTAD and energy metabolizability, no significant differences were observed among treatments (Table 6). Pigs fed local legume-based diets showed a significant reduction in urinary nitrogen excretion and a subsequent significant increase in both retained N/ingested N and retained N/digested N ratios (Table 6). This optimization in nitrogen utilization may indicate that alternative diets fit effectively with the ideal protein concept, allowing the animals to metabolize and retain amino acids as efficiently as in the standard soybean meal diet.

Table 9: Effect of dietary treatments on total tract apparent digestibility and nitrogen utilization in cosmopolitan pigs

	Dietary treatments				SEM	*P*-value
	Control	Pea	Chickpea	Lentil		
Dry matter TTAD	0.856	0.868	0.879	0.876	0.007	0.17
Organic matter TTAD	0.872	0.882	0.892	0.889	0.007	0.21
Gross energy TTAD	0.804	0.817	0.815	0.819	0.015	0.89
Energy metabolizability	0.823	0.837	0.845	0.845	0.008	0.22
ME intake (kJ/d)	19230	18310	20278	18904	985.9	0.56
N intake (g/d)	40.18	38.67	41.03	37.97	2.080	0.72
N in urine (g/d)	10.10^{a}	7.90^{b}	8.28^{b}	7.91^{b}	0.559	0.03

Nitrogen TTAD	0.804	0.817	0.815	0.819	0.015	0.89
N retention (g/d)	22.13	23.54	25.21	23.14	1.453	0.52
Retained N / ingested N	0.553[a]	0.610[b]	0.612[b]	0.607[b]	0.015	0.04
Retained N / digested N	0.688[a]	0.747[b]	0.751[b]	0.742[b]	0.015	0.03

Plasma biochemical parameters remained unaffected by dietary treatments. Calprotectin and myeloperoxidase levels did not increase confirming that the inclusion of 50% local legumes does not compromise gut inflammation.

Second trial: Iberian pigs
Like in conventional pigs, Iberian pigs fed local legume diets maintained growth performance, total feed intake, and gain/feed ratios fully comparable to the control group (Table 7). No significant variations were observed in nutrient TTAD or nitrogen balance, reinforcing the nutritional value and safety of these local ingredients, across different pig genetics.

Table 10: Effect of dietary treatments on productive parameters of Iberian pigs

	Dietary treatments				SEM	*P*-value
	Control	Pea	Chickpea	Lentil		
Initial BW, kg	32.1	33.1	33.2	33.1	1.33	0.92
Final BW, kg	73.4	73.9	74.0	75.6	2.45	0.93
ADG, g	820	810	810	842	34.9	0.90
Average intake, g/d	2775	2784	2717	2849	100.5	0.83
Gain/feed	0.296	0.291	0.297	0.296	0.006	0.88

Plasma biochemical analysis showed similar values among groups. A significant decrease in calprotectin levels for legume-fed groups compared to the control was revealed (Table 4). This suggests that replacing 50% of soybean meal protein with pea, chickpea, or lentil protein might
exert a protective effect on the gut mucosa of Iberian pigs, through lowering baseline intestinal inflammation.

Table 11: Effect of dietary treatments on markers of intestinal inflammation of Iberian pigs

	Dietary treatments				SEM	*P*-value
	Control	Pea	Chickpea	Lentil		
Calprotectin, ng/g	0.416[a]	0.241[b]	0.201[b]	0.173[b]	0.043	0.002
Myeloperoxidase, ng/g	146.8	140.1	149.8	149.7	12.64	0.94

Conclusions

Replacing 50% of soybean protein with local peas, chickpeas, or lentils, does not impair growth performance, nutrient digestibility, biochemical parameters or intestinal inflammation in cosmopolitan or Iberian pigs. These local legumes could be a sustainable substitute of soybean protein with some additional benefits over reduced N excretion and intestinal health.

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Dissemination:

(1) XXI Jornadas sobre Producción Animal, ISBN: 978-84-09-72522-9; Pag 66 Zaragoza, Spain, 3-4 June 2025 (Oral presentation)
LEGUMBRES DE DESTRÍO COMO ALTERNATIVA SOSTENIBLE A LA SOJA EN DIETAS PARA CERDOS EN CRECIMIENTO: PARÁMETROS PRODUCTIVOS Y BIOQUÍMICOS.

(2) XXI Jornadas sobre Producción Animal, ISBN: 978-84-09-72522-9; Pag 67 Zaragoza, Spain, 3-4 June 2025 (Oral presentation)
LEGUMBRES DE DESTRÍO COMO ALTERNATIVA SOSTENIBLE A LA SOJA EN DIETAS PARA CERDOS EN CRECIMIENTO: EFECTOS SOBRE LA DIGESTIBILIDADDE NUTRIENTES Y EL BALANCE DE NITRÓGENO.

(3) XXI Jornadas sobre Producción Animal, ISBN: 978-84-09-72522-9; Pag 102 Zaragoza, Spain, 3-4 June 2025 (Poster)
LEGUMBRES DE DESTRÍO COMO ALTERNATIVA SOSTENIBLE A LA SOJA EN DIETAS PARA CERDOS EN CRECIMIENTO: EFECTOS SOBRE LA HISTOLOGÍA INTESTINAL.

(4) 8th International Symposium on Energy and Protein Metabolism and Nutrition, Book of Abstracts IISEP 2025, Pag: 118 Rostock-Warnemünde, Germany 15-18 September 2025 (Oral Presentation)
Local legumes as a sustainable alternative to soya in growing Landrace × Large-White pig diets**.**

(5) EAAP Annual Meeting, Hamburg, Germany, 7-11 September 2026
(Oral presentation, accepted)
Alternative legumes as a sustainable replacement for soybean meal in Iberian pig diets: effects on growth performance and plasma metabolites

(6) EAAP Annual Meeting, Hamburg, Germany, 7-11 September 2026
(Oral presentation, accepted) Alternative legumes as a sustainable replacement for soybean meal in Iberian pig diets: effects on nutrient digestibility, nitrogen balance and inflammatory markers

(7) EAAP Annual Meeting, Hamburg, Germany, 7-11 September 2026
(Poster, accepted)
In vitro large intestinal fermentation of growing pigs fed lentil, chickpea and soybean diets

(8) EAAP Annual Meeting, Hamburg, Germany, 7-11 September 2026
(Poster, accepted) Faecal volatile fatty acids production in growing pigs fed local legumes partially replacing soybean meal as main dietary protein source

SBM substitution by legume- experiment Summary: Key Achievements

Study	Protein replacement strategy	Growth performance	Nutrient utilisation	Biochemical / gut-health effects	Main outcomes
PULS – Puławska pigs	100% replacement of SBM with faba bean or narrow-leafed lupine seeds	ADG not affected over the whole experimental period. Narrow-leafed lupine improved overall FCR, but growth was temporarily reduced during the grower phase.	No significant differences in apparent total tract digestibility of DM, CP, P or GE.	Most serum parameters unaffected. Some treatment-specific changes occurred in AST, bilirubin, glucose, urea and triglycerides.	Faba beans and narrow-leafed lupine can replace SBM without compromising overall growth, while potentially improving feed efficiency and carcass characteristics.
ADA – Commercial crossbred pigs	50 or 100% replacement of SBM protein with peas, chickpeas or lentils	SBM replacement maintained or improved growth performance. Peas gave the most consistent response and, under some conditions, improved final BW and ADG. ADFI and FCR were generally unaffected.	Pea diets showed the highest apparent digestibility, particularly for CP. Chickpea showed somewhat lower and more variable digestibility.	Health status was maintained. MPO was unaffected and only limited treatment-specific effects on calprotectin were observed. Changes in intestinal fermentation and morphology were moderate and depended on the legume and environmental conditions.	Peas, chickpeas and lentils can partially or completely replace SBM without impairing health or performance. Peas showed the most consistent nutritional response.
EEZ-CSIC – Cosmopolitan pigs	50% replacement of SBM protein with peas, chickpeas or lentils	Final BW, ADG, feed intake and gain/feed ratio were not significantly affected.	Nutrient TTAD was unaffected, but legume diets reduced urinary N excretion and increased retained N/ingested N and retained N/digested N, indicating improved N-use efficiency.	Plasma biochemical parameters were unaffected. Calprotectin and MPO did not increase, indicating no adverse effect on intestinal inflammatory status.	Local legumes can replace 50% of SBM while maintaining performance and improving N utilisation, with potential environmental benefits through reduced urinary N losses.
EEZ-CSIC – Iberian pigs	50% replacement of SBM protein with peas, chickpeas or lentils	Growth performance, feed intake and gain/feed ratio were comparable with SBM control.	No significant differences in nutrient TTAD or N balance were observed.	Plasma biochemical parameters not affected. Calprotectin was significantly reduced by all three legume diets, and MPO was unaffected, suggesting a possible beneficial effect on intestinal inflammatory status.	Local legumes are also suitable for native Iberian pigs, maintaining nutritional performance and potentially providing additional benefits for intestinal health.

Overall findings

Across studies, locally produced legumes successfully replaced part or all of the soybean meal protein without adversely affecting overall pig growth performance. The results were consistent across different genetic types and production conditions.

The strongest additional benefits were related to improved feed efficiency in some treatments, favourable nutrient digestibility—particularly with peas—and improved nitrogen-use efficiency with reduced urinary N excretion in conventional pigs. Biochemical and intestinal-health indicators generally confirmed the nutritional safety of the alternative diets, with some evidence of reduced intestinal inflammation in Iberian pigs.

Overall, the studies support locally produced peas, chickpeas, lentils, faba beans and narrow-leafed lupins as viable alternatives to imported soybean meal, contributing to more locally based and potentially more sustainable European pig-feeding systems.

1.2. Inclusion of dried berry pomace in diets for fattening pigs

1.2.1. Study at Poznań University of Life Sciences (PULS)

By-products from the agri-food industry require sustainable management strategies to minimise their environmental impact. Fruit pomaces are particularly promising because they are rich sources of nutrients and bioactive compounds with potent antioxidant properties. Dried chokeberry pomace contains pectins that support digestive function, together with organic acids that exhibit anti-inflammatory activity and beneficial effects on lipid metabolism. Furthermore, its high soluble fibre content exerts a prebiotic effect by promoting the growth of beneficial gut microbiota. Similarly, blackcurrant pomace has been shown to modulate the composition and metabolic activity of the intestinal microbiota, thereby limiting undesirable fermentation processes and reducing the production of potentially harmful metabolites. These effects not only enhance animal health and gut function but may also contribute to reducing GHG emissions from livestock production.

Objectives

The aim of the study was to apply innovative feeding strategies involving the inclusion of dried blackcurrant and chokeberry pomaces in pig diets, in order to determine their effects on production performance, nutrient digestibility, and the excretion of environmentally harmful components, as well as to assess their potential to reduce GHG emissions.

Methods

The experiment was conducted on a commercial farm. A total of 90 pigs (30 per group; 15 females and 15 males) of initial BW of approximately 28 kg were housed on straw bedding and allocated to 3 dietary treatments. The control group (CON) was fed a standard commercial diet, whereas the experimental groups received diets supplemented with 7% of dried blackcurrant (BCP group) or dried chokeberry (CP group) pomaces during two feeding phases. The pigs were maintained under good welfare conditions for 107 days. After reaching approximately 40 kg body weight, 8 animals from each group (4 females and 4 males) were transferred to metabolic cages for two days to determine apparent total tract digestibility (ATTD) coefficients of dry matter (DM), crude protein (CP), phosphorus (P) and gross energy (GE), and nitrogen balance using the total collection method. Feed intake, as well as faeces and urine output were measured, and representative samples were collected for analysis. Subsequently, the animals were moved to respiration chambers to assess GHG production. After reaching approx.115 kg body weight, 10 pigs from each group (5 females and 5 males) were slaughtered. Post-mortem carcass measurements were performed, and blood, fat, and meat samples were collected for further analysis. Statistical analyses were performed using one- and two-way analyses of variance (ANOVA), followed by Duncan's test at $P \leq 0.05$.

Results and Discussion

Fruit pomaces are rich sources of crude fibre. The addition of blackcurrant and chokeberry pomaces at 7% increased the crude fibre content in the diet. The inclusion of berry pomaces significantly increased ($P<0.05$) weight gains of pigs during the finisher phase but had no effect on overall growth throughout the entire experimental period ($P>0.05$). Supplementation with chokeberry pomace significantly increased ($P< 0.05$) feed conversion ratio (FCR) during the finisher phase; however, FCR over the entire period was similar across all groups and did not exceed 3 kg/kg (Table 8).

Table 12. Effect of including Blackcurrant or Chokeberry by-products on performance characteristics

Period	***Group***	*Control*	*Blackcurrant*	*Chokeberry*	*P-value*
	Initial BW (kg)	27.9	28.5	28.0	NS
Grower	BW (kg)	78.0	80.2	79.5	NS
	Gain (kg)	50.1	51.8	51.5	NS
	Daily gain (kg)	0.84	0.86	0.86	NS
	FI/pig (kg)	132.3	137.9	131.5	NS
	FCR (kg/kg)	2.68	2.70	2.60	NS
Finisher	BW (kg)	122.3	126.3	127.3	NS
	Total gain (kg)	44.3^{b}	46.1^{a}	47.8^{a}	P<0.05
	Daily gain (kg)	0.94^{b}	0.98^{a}	1.02^{a}	P<0.05
	FI/pig (kg)	138.3	144.6	161.7	NA
	FCR (kg/kg)	3.22^{b}	3.16^{b}	3.41^{a}	P<0.05
Total	Gain (kg)	94.4	97.8	99.3	NS
	Daily gain (kg)	0.88	0.91	0.93	NS
	FI/pig (kg)	270.6	282.6	293.2	NS
	FCR (kg/kg)	2.89	2.91	2.98	NS

The addition of blackcurrant and chokeberry pomaces to the finisher diets did not negatively affect growth performance and even slightly increased the final body weight of pigs ($P > 0.05$) by approximately 4–6 kg compared with the control group. Pomaces inclusion did not negatively influence the ATTD of pig diets. ATTD coefficients of CP, P, and GE were similar in the CON and CP groups, whereas in the BCP diet they were higher (Figure 1; $P>0.05$).

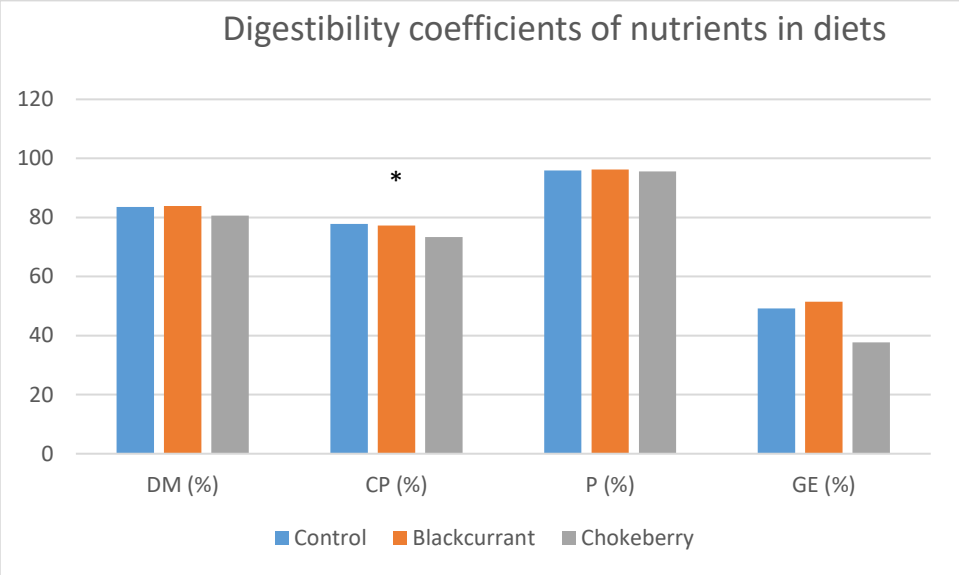


Figure 1. Nutrient digestibility of experimental diets (* means statistically significant differences at p<0.05).

The pigs in BCP group had lower N content in faeces and the highest N ret/N intake ratio (P < 0.05). Nitrogen digestibility (g/d) and retention was similar across all groups. Data obtained from respiration chambers further indicated the potential to reduce methane and ammonia emissions from pigs fed diets supplemented with berry pomaces (Table 9).

Table 13. Comparison of GHG emissions from pigs fed the experimental diets.

GHG/group	CON	BCP	CP
CO_2 g/day/pig	532	581	575
CH_4 g/day/pig	1.70	1.58	1.52
NH_3 g/day/pig	0.04	0.03	0.03

Conclusions

The results highlight both the potential of including by-products from fruit industry in pig feeding as part of strategies to mitigate climate change.

Dissemination:

(1) EAAP-ASAS Conference on Livestock farming and the environment: emissions and solutionsBook of Abstracts No. 40 (2026) Angra do Heroísmo – Terceira Island (Azores), Portugal, 19-21 April, 2026 (Poster 29) Environmental and production aspects of the use of dried berry pomace in the feeding of fattening pigs.

1.3. Low-Protein Diet Research in Growing-Finishing Pigs

1.3.1. Studies at Swine Research Group, Agroscope, Switzerland

Three complementary experiments have been conducted to evaluate low-protein (LP) diets as a sustainable feeding strategy for growing-finishing pigs. Research progressed from testing the interaction between LP diets and pen hygiene conditions (VIPO-51), to optimizing essential amino acid (EAA) supplementation under stress (VIPO-52), to incorporating circular and alternative protein ingredients (VIPO-53). Collectively, these trials demonstrate that LP diets effectively reduce environmental impact while maintaining or improving pork quality, provided that amino acid supply is carefully balanced.

Experiment 1: VIPO-51 – Low protein diets under contrasting hygiene conditions

Design

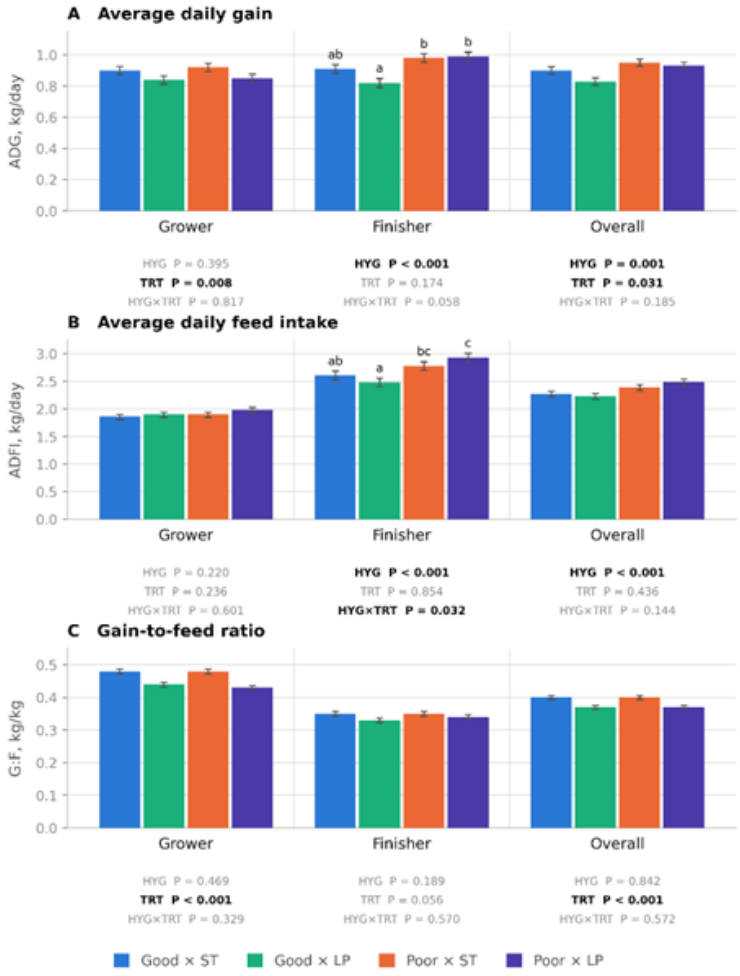
48 Swiss Large White female pigs (23.5 ± 2.24 kg initial BW) were used
• Two hygiene conditions: good (daily cleaning) vs. poor (twice-weekly cleaning) were tested
• Two diets: standard (ST) with 16.4% CP (grower), 12.5% (finisher) vs. low-protein (LP) with 20% CP reduction were tested
• Three outcome measures: growth/carcass, meat quality, ammonia emissions

KEY FINDINGS

Growth Performance & Carcass Quality (Fig. 2 A-C)

• LP diets reduced average daily gain but improved protein deposition efficiency
• Poor hygiene increased feed intake and growth rate but reduced protein efficiency
• Combined stressor (poor hygiene + LP) altered plasma amino acid profiles and suppressed immune markers (lower white blood cells, especially lymphocytes)

Outcome: LP diets provide positive results but require using specific amino acid optimization under stress conditions



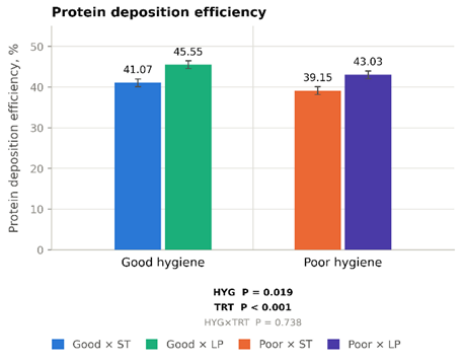


Figure 2. Growth performance (A–C) and protein deposition efficiency (D) of growing-finishing pigs fed standard or low-protein diets under good or poor room hygiene

Meat Quality (Fig. 3)

- LP diets increased intramuscular fat level by 23%
- Technological quality improved: 11.8% lower shear force, reduced moisture losses during aging
- Poor hygiene enhanced sensory traits (tenderness +22%, juiciness +23.5%)

Outcome: LP diets maintain or enhance pork palatability and marbling

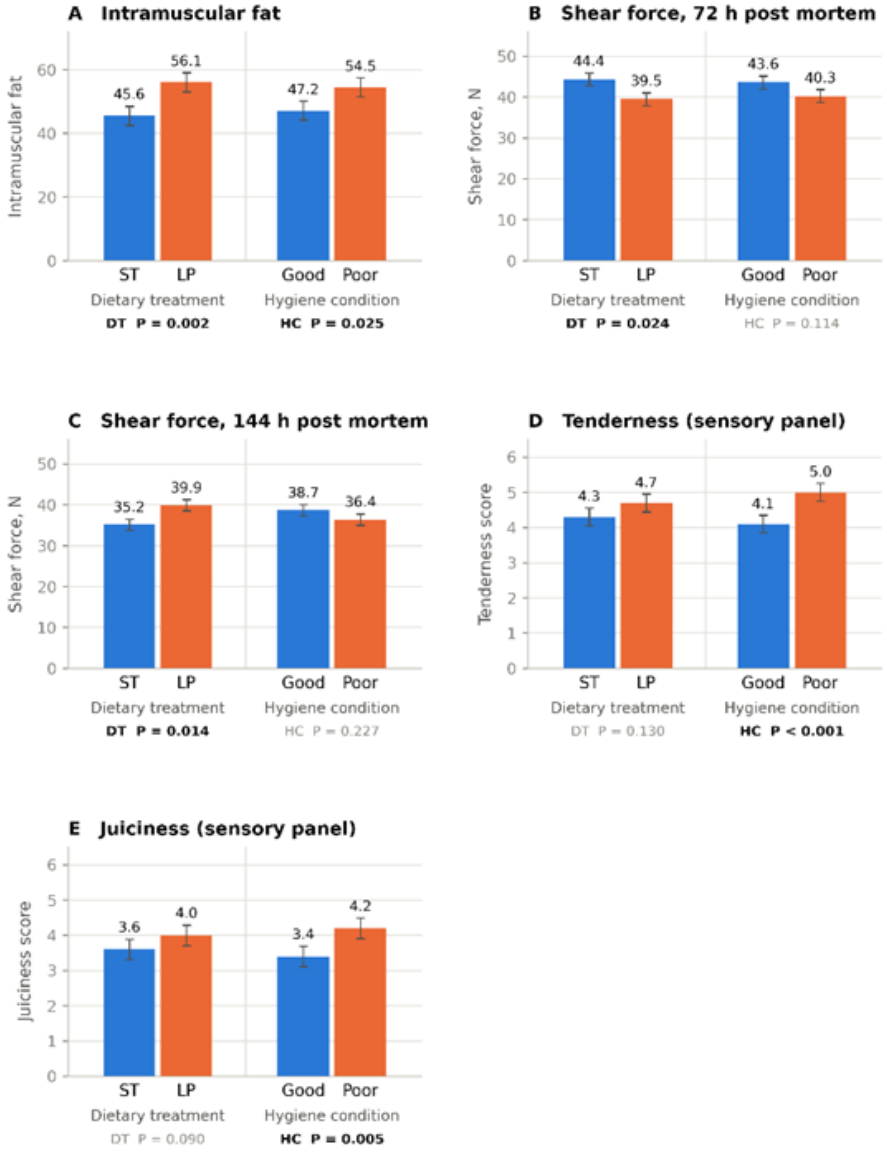


Figure 3. Meat quality (A-C) and sensory (D-E) traits of growing-finishing pigs fed standard or low-protein diets under good or poor room hygiene

Ammonia & Slurry Emissions (Fig. 3)

- LP diets lowered nitrogen excretion and reduced in vitro ammonia production
- Ammonia peak was 38% lower and delayed, providing management flexibility
- Benefits held across hygiene conditions

Outcome: LP diets reliably reduce environmental impact

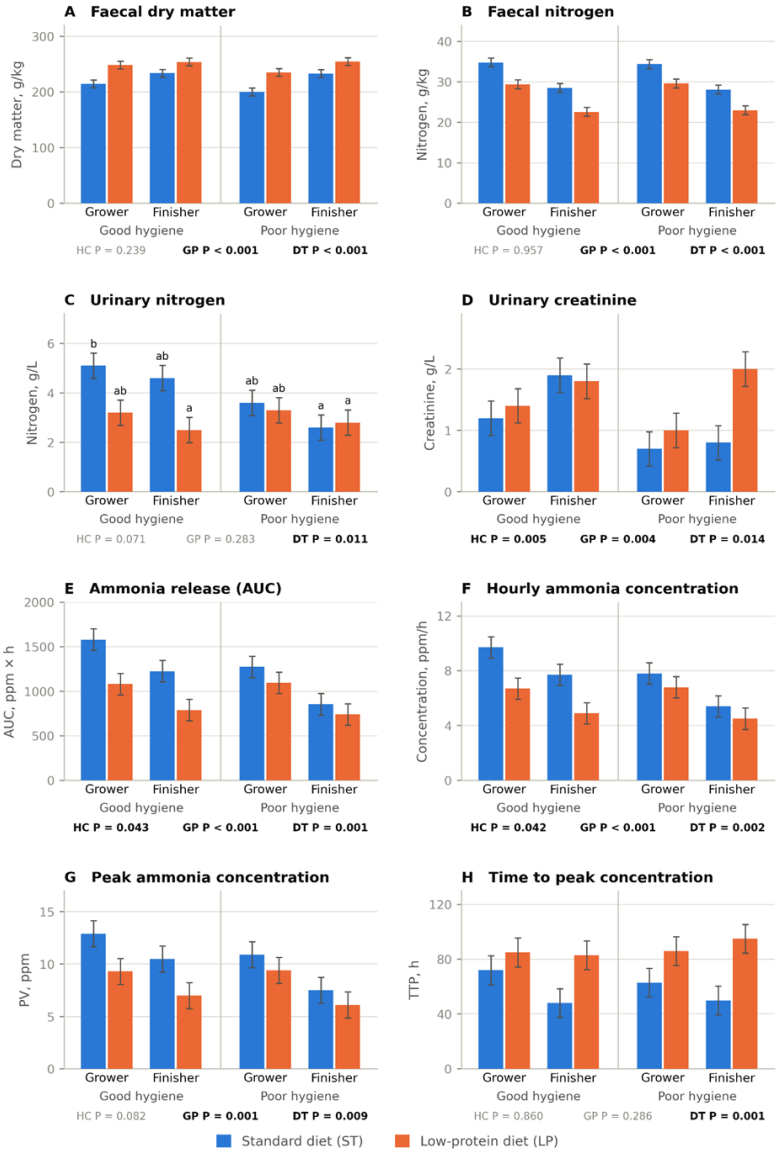


Figure 4 Excreta composition (A-D) and ammonia release (E-H) in growing-finishing pigs fed standard or low-protein diets under good or poor room hygiene

Implications

Low-protein diets in commercial pig production represent an effective sustainability strategy. However, diet formulation must prioritize essential aminoacids (EAA) to support protein deposition and prevent excess fat accretion, especially under poor hygiene stress.

Experiment 2: VIPO-52 – Graded EAA Supplementation Optimization

Design

48 Swiss Large White pigs (~20 kg initial BW) were used
- Four dietary treatments: SCP-LP, NSCP-LP, NSCP-LP+, NSCP-LP++
- Three LP diet formulations differing in EAA (Lys, Met, Thr, Trp, Val) supplementation:
- LP: 20% below requirements (80%)
- LP+: meeting requirements (100%)
- LP++: 20% above requirements (120%)
- Both strict (SCP) and non-strict (NSCP) cleaning protocols

Trial ran Feb–June 2025

KEY FINDINGS

Growth & Feed Efficiency (Fig. 5 A-C)

- EAA supplementation to requirements (LP+) reduced total feed intake by 4.2% and shortened time on feed by 3.5 days ($P \leq 0.018$)
- Feed efficiency improved 4.1% with adequate EAA ($P = 0.010$)
- Average daily gain unchanged across treatments

- Hygiene condition (daily vs. weekly cleaning) had no significant effect on performance

Nitrogen Utilization (Fig. 5 D)

- Despite 2.9% lower CP intake, LP+ and LP++ pigs maintained similar carcass protein content as LP pigs
- Nitrogen deposition efficiency improved 6.5% with EAA supplementation ($P \leq 0.015$)
- Urinary nitrogen tended lower; urinary N:creatinine ratio significantly reduced ($P = 0.015$)

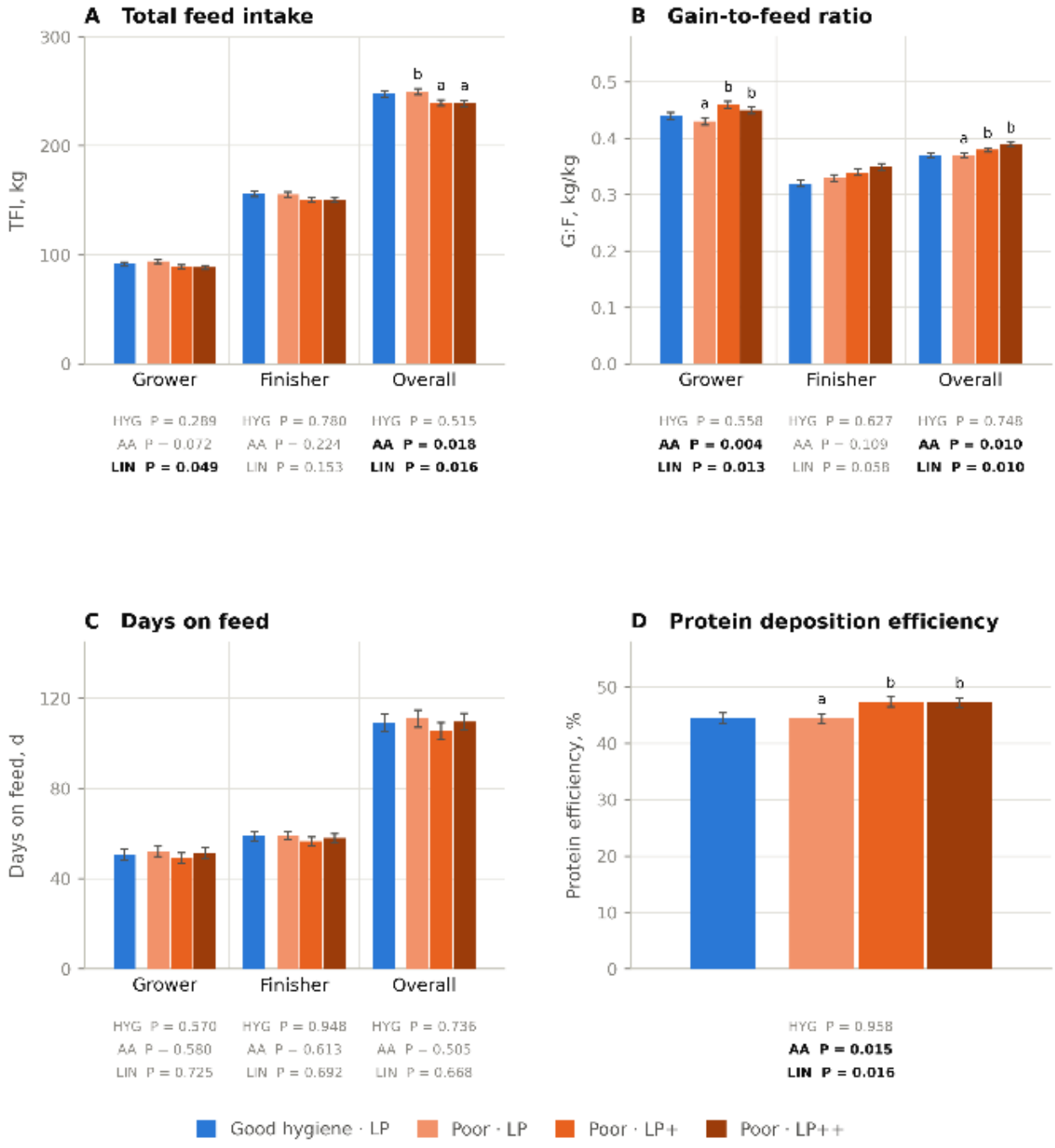


Figure 5. Growth performance (A-C) and protein deposition efficiency (D) of pigs fed low-protein diets with graded amino acid supplementation

Ammonia Production (Fig. 6)

- In vitro ammonia 38.2% lower in LP+ and LP++ vs. LP ($P \leq 0.034$)
- Ammonia peak 38% lower; timing delayed 43.3 hours
- CRITICAL FINDING: No difference between LP+ and LP++ — meeting requirements sufficient

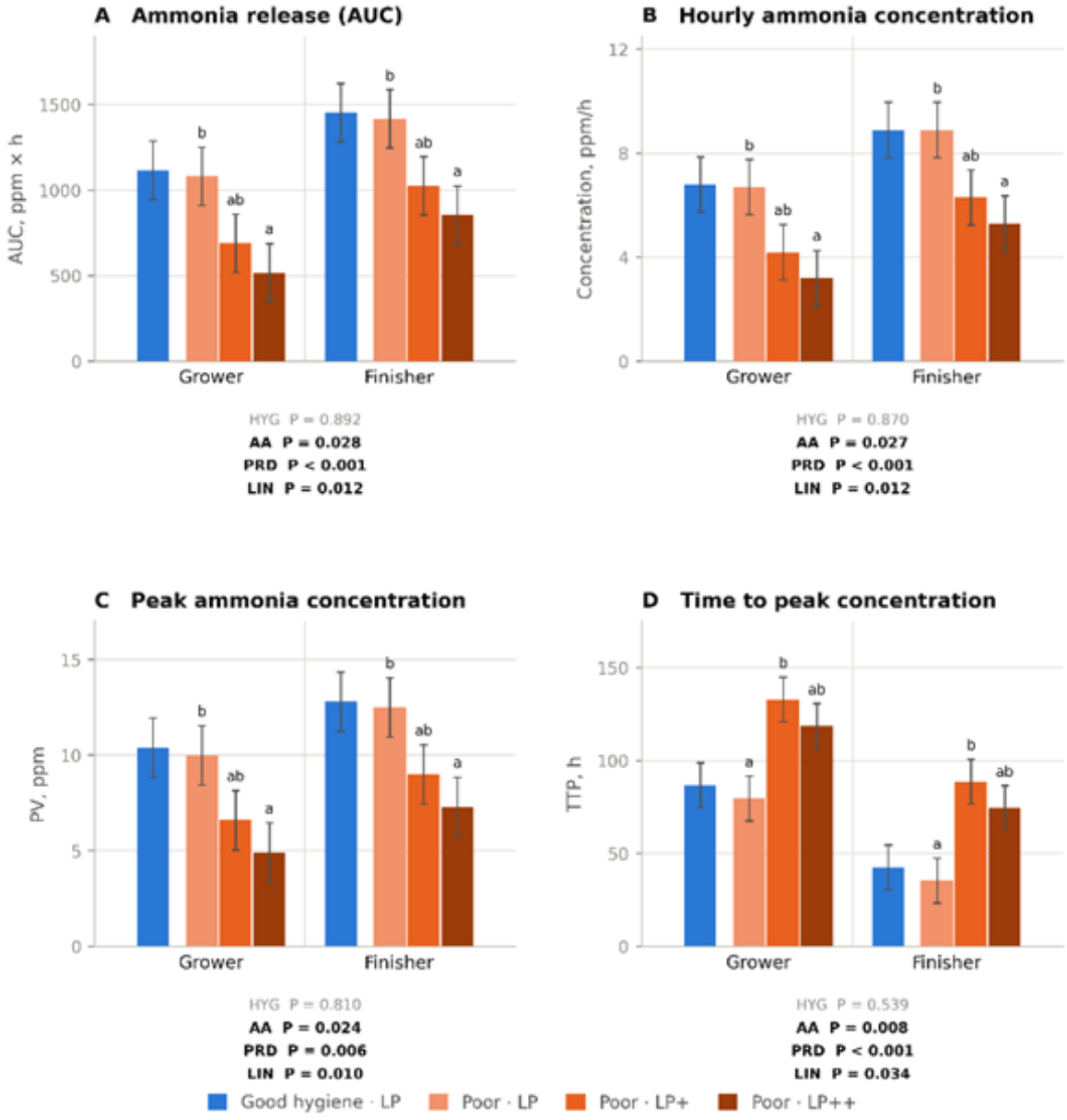


Figure 6. Growth performance (A-C) and protein deposition efficiency (D) of pigs fed low-protein diets with graded amino acid supplementation

Hygiene Interactions

Poor hygiene did not significantly affect growth, feed efficiency, or nitrogen utilization.
Results suggest adequate amino acid supply (LP+) is the key limiting factor, not hygiene *per se.*

Implications

Meeting EAA requirements in LP diets (100% of recommendations; LP+) is sufficient to optimize feed efficiency, nitrogen utilization, and markedly reduce ammonia emissions. Supplementation above requirements provides no additional benefit. Pen hygiene remains important for welfare, but adequate EAA balance is the primary performance driver under stress.

Cross-Experiment Summary: Key Achievements

Aspect	VIPO-51	VIPO-52
Aim	LP diet effects under hygiene stress	Optimize EAA supplementation
Status	in review/ready for submission	EAAP 2026 presentation
Main Finding	LP effective but needs amino acid balance	100% EAA requirements sufficient
Ammonia Reduction	~38% vs. standard	~38% vs. inadequate EAA
Protein Efficiency	+6.6% vs. standard	+6.5% vs. inadequate EAA

Overall Implications

1. Efficacy of Low-Protein Diets: Low-protein feeding strategies effectively reduce nitrogen excretion and ammonia emissions (38% reduction documented in VIPO-51 and VIPO-52). These benefits are robust across varying hygiene conditions.
2. Amino Acid Supply is Critical: The key to LP diet success is meeting EAA requirements through targeted supplementation or ingredient selection. Inadequate EAA supply increases variability and limits benefits. Supplementation above requirements provides no additional advantage.
3. Environmental and Production Benefits Coexist: The LP diets simultaneously achieve environmental gains (lower N excretion, ammonia reduction) and production benefits (improved protein efficiency, maintained growth, enhanced meat quality including marbling).
4. Practical Implementation: Results from VIPO-51 and VIPO-52 support LP diet adoption across diverse production systems. Pen hygiene remains important for overall welfare but is not the limiting factor for LP diet performance when amino acid balance is adequate.

Conclusion

These research series provide robust evidence that LP diets represent a practical, effective strategy to improve the sustainability of pig production without compromising growth performance or meat quality. Success depends on meeting EAA requirements through careful diet formulation.

1.4. Insect protein as substitute for soyabean protein

1.4.1. Studies at Spanish National Research Council (EEZ-CSIC)

Introduction

In recent years growing attention has been given to alternatives to soy as a result of increasing market prices, ethical and environmental concerns, and competition for land resources between animal feed and human food production. Furthermore, these alternatives could help reduce Europe's reliance on third-country imports for livestock feed (1). Insect meals represent a valuable alternative with potential to partially or totally replace soyabean protein (2). As European intensive swine production systems rely heavily on concentrated feeds, the substitution of soy with alternative protein sources is considered a good option to reduce GHG emissions from swine production (3).

Objectives

The studies aimed at assessing the effects of replacing 100% soybean protein with insect protein from *Hermetia illucens* and *Tenebrio molitor* meals in terms of growth performance, total tract apparent digestibility (TTAD) of nutrients, N balance, biochemical parameters and intestinal inflammation in cosmopolitan pigs.

Methods

All diets were isoenergetic and isoproteic, with similar digestible lysine/essential amino acid ratios and nutritionally balanced for growing pigs.

Thirty (Duroc × Pietrain) × (Landrace × Large-White) pigs were randomly assigned to three experimental groups: a control group fed a soybean meal based diet and two groups in which 100% of soybean protein was replaced with protein from *Hermetia illucens* or *Tenebrio molitor* meals, respectively. Initial BW was 17 ± 0.8 kg, and final BW 62 ± 2.4 kg. After 3 weeks, TTAD of nutrients and nitrogen balance experiments were carried out in 6 animals per treatment. Individual feed consumption was recorded and feces and urine individually quantified and collected over 4 days to obtain a representative sample. 8 weeks after the beginning of the trial, the animals were slaughtered and blood samples taken to analyze biochemical parameters. Faeces samples from the colon were taken to determine markers of intestinal inflammation.

Analysis of variance was performed to study the effect of treatments on the evaluated parameters using the STATGRAPHICS Centurion XVI statistical package version 16.1.18 (StatPoint Technologies Inc., Warrenton, VA). Pig was the experimental unit and significance level was set at 0.05.

Results and Discussion

Total replacement of soybean protein with insect meal protein did not led to significant variations in growth performance between control and pig fed insect meal diets (Table 9) although pigs fed *Hermetia illucens* showed the highest average daily gain and feed efficiency than the *Tenebrio molitor* group. These differences in growth performance cannot be attributed to diet palatability as average daily intake remained unchanged between the three groups.

Table 14: Effect of dietary treatments on productive parameters of growing pig fed insect meal diets

	Dietary treatment			SEM	*P*-value
	Control	Hermetia	Tenebrio		
Initial BW, kg	17.2	17.2	17.2	0.770	0.996
Final BW, kg	62.3	65.3	58.5	2.39	0.15
ADG, g	848 [ab]	926 [b]	749[a]	34.9	0.005
Average intake, g/d	1625	1640	1509	202.3	0.30
Gain/feed	0.523[b]	0.565[a]	0.496[c]	0.022	0.001

Despite some productive differences, no significant alterations were detected in dry matter, organic matter, or energy TTAD, nor were there significant changes in N retention or efficiency (Table 10).

Table 15: Effect of dietary treatments on total tract apparent digestibility and nitrogen utilization in growing pig fed insect meal diets

	Dietary treatment			SEM	*P*-value
	Control	Hermetia	Tenebrio		
Dry matter TTAD	0.884	0.870	0.874	0.015	0.19
Organic matter TTAD	0.896	0.880	0.885	0.014	0.09
Gross energy TTAD	0.879	0.860	0.868	0.015	0.06
ME intake (kJ/d)	22276	22168	22380	1646.4	0.97
N excreted in urine (g/d)	11.6	9.8	12.6	3.43	0.29
Nitrogen TTAD	0.848	0.824	0.816	0.029	0.09
N retention (g/d)	23.7	27.2	23.1	3.82	0.09
Retained N / ingested N	0.569	0.606	0.529	0.081	0.19
Retained N / digested N	0.672	0.735	0.647	0.093	0.17

Regarding biochemical parameters, a significant decrease in plasma albumin was observed in the *Tenebrio molitor* group compared to both the control and *Hermetia illucens* groups. No other systemic or intestinal inflammatory markers were altered. In the present experimental conditions, *Hermetia illucens* meal seem an excellent candidate for soybean replacement in terms of growth and metabolic performance.

Conclusions

Replacing soybean protein with protein from *Hermetia illucens* or *Tenebrio molitor* does not impair growth performance, nutrient digestibility, biochemical parameters or intestinal inflammation in growing pigs.

Dissemination:

(1) EAAP Annual Meeting, Hamburg, Germany, 7-11 September 2026
(Poster, accepted) Insect protein as a sustainable replacement for soybean meal in diets for growing pigs: effects on growth performance, plasma metabolites and gut inflammation

References

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2. Novel feeds to lower the carbon footprint of beef production

The livestock sector faces increasing pressure to reduce its environmental footprint while maintaining productive efficiency to meet the growing demand for animal-derived foods. Intensive beef production systems are no exception, with feed production being one of the main contributors to GHG emissions, land occupation, water use, and fossil energy consumption. Hence, improving feed formulation has become one of the most effective strategies for increasing the sustainability of beef production (de Vries et al., 2015; Putman et al., 2023).

Typical finishing diets rely on SBM as the primary protein source because of its high protein concentration and favorable amino acid profile. However, European beef production remains highly dependent on imported soybean and soybean-derived products, mainly from North and South America, increasing the environmental burden associated with land-use change, deforestation and long-distance transport, while also exposing production systems to fluctuations in global feed markets (FAO, 2023). Reducing this dependency through greater protein autonomy has therefore become a priority for improving both the sustainability and resilience of livestock production. Different nutritional strategies have been proposed to reduce the inclusion of imported soybean without compromising animal performance. These include the greater use of locally produced cereals, agro-industrial co-products such as sugar beet pulp, optimized inclusion of alternative protein sources such as DDGS, and precision nutrition approaches based on rumen-protected essential amino acids to match metabolizable protein requirements better (Wilkinson, 2011; Lee et al., 2012; Mottet et al., 2017;). Rather than relying on a single substitute, combining complementary feed ingredients offers the opportunity to formulate diets that reduce the environmental footprint of feed while maintaining productive efficiency. The evaluation of these alternative feeding strategies has also benefited from recent advances in Precision Livestock Farming (PLF). Automated feeders, drinkers, and walk-over weighing systems allow continuous and non-invasive monitoring of individual feed intake, water consumption, body weight, and feeding behavior under commercial conditions. These technologies improve feeding management, reduce feed wastage, support animal welfare and generate high-resolution phenotypic data that facilitate a more accurate assessment of nutritional interventions than conventional performance measurements alone (Berckmans, 2017). Combined with Life Cycle Assessment (LCA), PLF provides a comprehensive framework for evaluating both the productive and environmental consequences of alternative feeding strategies.

2.1. Use of a combination of ingredients and lower protein levels to reduce the use of soya bean products in intensive beef fattening system in Spain (CSIC and AEANI)

This study aimed to evaluate soybean meal-free finishing diets formulated by combining locally produced cereals, sugar beet pulp, different levels of DDGS and, in one treatment, rumen-protected Lysine and Methionine, in Avileña-Negra Ibérica bulls managed under commercial feedlot conditions in Spain. We hypothesized that reducing the reliance on imported soybean-derived ingredients through locally available feed resources, supported by precision nutrition and PLF-based monitoring, would maintain productive performance while improving the environmental sustainability of intensive beef finishing systems.

Methodology

Animals, Housing, and Dietary Treatments

Animals were handled and cared for by trained personnel according to the Spanish Animal Experimentation guidelines (RD 53/2013). The experimental protocol was approved by Junta de Castilla y Leon committee (1684/2024). The experiment was conducted at the RAEANI commercial feedlot (Riocabado, Spain). A total of 80 Avileña-Negra Ibérica bulls with an initial body weight (BW) of 330 ± 14.8 kg (mean ± SD) were enrolled in the study. The study was conducted as a randomized complete block design (RCBD), with bulls blocked according to initial BW and age, and randomly assigned within block to one of four dietary treatments. The finishing diets (Table 11) were: a commercial control diet that included imported soybean meal (SBM) and soybean oil (Control), and three alternative diets that excluded SBM and instead relied on a combination of local cereals and beet pulp to replace the removed protein and energy, together with proportional reductions in soybean oil and DDGS inclusion relative to Control. Diet A included rumen-protected Lys and Met and reduced soybean oil and DDGS by 11.5% and 44.0%, respectively; Diet B reduced soybean oil and DDGS by 34.6% and 24.7%, respectively, without amino acid supplementation; and Diet C reduced soybean oil and DDGS by 11.5% and 47.3%, respectively, also without amino acid supplementation.

Table 16. Ingredient composition of the concentrate of the experimental diets.

Item	Control	Diet A	Diet B	Diet C
Forage: concentrate ratio	20:80	20:80	20:80	20:80
Ingredient, % DM				
Barley[1]	43.1	22.6	25.2	26.6
Corn[1]	23.4	45.0	45.0	45.0
DDGS[2]	15	8.40	11.3	7.90
Wheat bran[1]	6.34	11.9	3.80	1.40
Soybean meal 47%	3.48	-	-	-
Soybean oil	2.62	2.30	1.70	2.30
Beet pulp	-	4.60	8.20	10.6
Beet molasses	2.00	2.00	2.00	2.00
Soybean hull	1.39	0.45	-	-
Lys[4]	-	0.16	-	-
Met[4]	-	0.16	-	-
Calcium carbonate	1.51	1.30	1.50	1.60
Sodium bicarbonate	0.50	0.50	0.50	0.50
Dicalcium phosphate	-	-	-	1.30
Salt	0.30	0.30	0.40	0.40
Calf premix	0.30	0.30	0.30	0.20

[1] National origin
[2] DDGS: dried distillers grains with solubles from corn
[3] U.S.A origin
[4] Rumen protected
Control: commercial control diet, including imported soybean meal (SBM) and soybean oil. Diets A, B and C excluded SBM and relied on cereals and beet pulp to replace the removed protein and energy. Diet A: 11.5% reduction in soybean oil and 44.0% reduction in DDGS relative to Control, with rumen-protected Lys and Met. Diet B: 34.6% reduction in soybean oil and 24.7% reduction in DDGS relative to Control, without amino acid supplementation. Diet C: 11.5% reduction in soybean oil and 47.3% reduction in DDGS relative to Control, without amino acid supplementation.

Table 17. Average chemical composition of the experimental diets throughout the experiment.

	Concentrate				Wheat Straw
Item	Control	Diet A	Diet B	Diet C	
DM, %	91.3	90.8	90.7	92.2	91.4
OM, % DM	93.3	94.0	94.1	92.9	62.6
Crude protein, % DM	15.2	13.7	13.2	11.9	4.40
Neutral detergent fiber, % DM	20.7	28.7	26.4	21.2	77.8
Acid detergent fiber, % DM	7.79	5.94	5.75	5.64	45.6

Ether extract, % DM	5.56	5.43	4.15	5.34	1.04
Ash, % DM	6.67	5.95	5.91	7.07	7.38
Gross energy, MJ/kg DM	17.2	17.2	17.1	16.7	17.8

Feeding, Drinking, and Body Weight Monitoring

Concentrate and water intake were measured throughout the experiment using an automated feeder and drinker platform combining RFID-based individual identification with automated feed and water weighing. The system continuously captured individual visit events and feed or water disappearance at each feeder interaction, allowing calculation of intake, visit frequency, feeding patterns, and temporal feeding behavior. Furthermore, walk-over scales continuously recorded intake behavior and body weight.

Sample Collection

Straw and concentrate samples were collected bimonthly and stored for chemical analyses. Also, feed and refusals (i.e., straw and concentrate), and fecal samples were collected at the end of the experiment to determine apparent total-tract digestibility of nutrients. A known amount of straw was offered daily to each pen, and refusals were weighed to estimate straw intake. Concentrate intake continued to be recorded using the automatic feeding system as previously described. Fecal samples were collected directly from the rectum. Apparent digestibility coefficients will be estimated using lignin as an internal marker. Feed, refusals, and fecal samples were analyzed for chemical composition. Digestibility coefficients of DM, OM, CP, NDF, and ADF will be subsequently calculated. Straw, concentrate, and fecal samples were dried and ground to pass through a 1-mm sieve for further chemical analysis. Dry matter (method 934.01) and organic matter (OM, method 942.05) were determined according to AOAC (2005). Crude protein (CP) was calculated by multiplying by 6.25 the N content (AOAC method 990.03) determined using the Dumas method (Leco TruSpec CN, St. Joseph, MI, USA). Ether extract (EE) was measured by petroleum ether extraction (AOAC method 920.39). Neutral detergent fiber (NDF) and acid detergent fiber (ADF) were determined following Van Soest et al. (1991) using an Ankom 220 fiber analyzer unit (Ankom Technology Corp., Macedon, NY, USA), with a heat-stable α-amylase. Acid detergent lignin (ADL) was determined by the solubilization of cellulose with 72% sulfuric acid. Furthermore, the gross energy (GE) content was determined using an oxygen bomb calorimeter (Model 6100 compensated jacket, Parr Instruments Co., Moline, IL).
At the end of the experiment, a blood sample (5 mL) was collected by jugular venipuncture into serum Vacutainer tubes (Becton Dickinson, Franklin Lakes, NJ). Samples were centrifuged at 2,500 × g for 15 min at 4 °C and were harvested and stored at −20 °C until analysis. Furthermore, carcass measurement was recorded at the slaughter house to asses carcass quality.

Environmental Impact Assessment

The present study was conducted in accordance with the UNE-EN ISO 14044 standards (ISO, 2006), which provide a harmonized framework for conducting Life Cycle Assessments (LCA) in ruminant supply chains. The assessment examined the environmental impacts of four dietary treatments evaluated during an *in vivo* trial mentioned in the above section 2.1. The methodological workflow comprised four different stages: (1) primary data collection; (2) calculation of inputs for LCA; (3) environmental impact assessment, including on-farm emissions and direct land use change (LUC); and (4) final interpretation and discussion of the outcomes.
Data collection

Recorded parameters at the feedlot encompassed feed ingredients, inclusion rates, nutrient composition, feed and forage intake, and animal performance parameters, such as growth rates and average daily gain (ADG). Gross energy intake was calculated based on the dietary gross energy content of the diet alongside the daily consumption of both feed and forage. Subsequently, the compiled datasets were converted into LCA inputs, quantified as energy and material flows, and structured for modelling using SimaPro v9.3. To model the background processes, Ecoinvent 3.0 and Agri-footprint inventory databases were used. The comprehensive life cycle inventory of feed ingredients, normalized per functional unit (FU), is detailed in Table S1.

Functional unit and system boundaries
The FU for this study was defined as 1 kg of liveweight (LW) gain at the farm gate, corresponding to the primary product prior to slaughterhouse processing. The temporal boundary encompassed the fattening period to estimate the average environmental impacts of beef production. A cradle-to-farm-gate system boundary was implemented, including all operations up to the point when the bulls left the feedlot. The evaluated processes included on-farm activities (e.g., enteric fermentation, manure management, fuel and electricity use, and animal housing) as well as off-farm processes (e.g., crop cultivation, feed manufacturing, forage processing and transportation). This specific boundary was selected because feed production and on-farm bull production are the dominant contributors to most impact categories in beef LCA. Furthermore, post-farm gate stages, such as slaughterhouse processing, retail distribution, and consumer phase, introduce significant variability and uncertainty into the environmental assessment (de Vries et al., 2015; Notarnicola et al., 2017; Putman et al., 2023).

Life cycle inventory
All of the inputs data used for the LCA are shown in Table 3. Enteric methane (CH_4) emissions were estimated using a Tier 2 modelling framework to ensure the biological robustness of the system-level estimations. The primary approach relied on the Tier 2 framework from the updated IPCC guidelines (IPCC, 2019), applying a default CH_4 conversion factor (*Ym*) of 4.00% of gross energy intake for fattening bulls. To perform a sensitivity analysis and compare these estimations with methodologies based on specific feed nutrient composition, empirical equations developed by van Lingen et al. (2019) for lower forage diets were applied. Specifically, the DMI_NDF_C and DMI_EE_C linear regression models were utilized to evaluate the daily CH_4 production. For these predictions, the NDF and EE contents of the concentrates and straw were obtained from Table 2, and subsequently calculated as a weighted percentage of total dietary DM based on their inclusion ratio. Daily DM intake was determined using primary physiological and performance data monitors during the *in vivo* trial. The feed energy digestibility (DE, expressed as a percentage of feed gross energy) was calculated on a DM basis from the percentage of total digestible nutrients (TDN, %). The dietary TDN content was predicted from the proximal chemical composition of the concentrates and forage (including CP, CF, NDF, ADF, ADL, and ashes) following the equations of the NRC, (2007). This specific DE value was subsequently integrated into the Tier 2 equations of the IPCC (2019) to calculate the daily excretion of volatile solids (VS) required for the downstream manure management inventory.

To estimate CH_4 and nitrous oxide (N_2O) emissions from manure management, IPCC Tier 2 equations (IPCC, 2019) were applied, utilizing a maximum CH_4-producing capacity (*Bo*) of 0.18 m^3 CH_4 per kg volatile solids for high-productivity animals. To capture the temporal and regional dynamics of manure handling on the farm, a weighted mass-balance partition approach was applied based on the actual operations schedule of the trial in Ávila from January to September. The animals were housed in a confinement system with straw bedding, which was completely cleared and renewed every 21 days based on direct operational records from the experimental facility. Given the continuous excretion pattern of the fattening bulls, the average residence time of manure under the animals (periodic bedding) was calculated as 10.4 days. Following removal, the manure was transported to a solid storage facility. Based on these weighted residence times, the manure management inventory was partitioned into two parallel, sequential systems: 14% was allocated to periodic bedding (<1 month accumulation) and 86% to solid storage. Taking these operations into account, a CH_4 conversion factor (MCF) of 6.50 % was selected, corresponding the temperate-climate default value for periodic bedding and reflecting the regional conditions during the monitoring period. For the solid storage phase, an MCF of 4.00% was

applied, corresponding to solid storage under temperate dry climate conditions. Direct N_2O emissions (EF_3) were set at 0.010 kg N_2O-N per kg N excreted for both the periodic deep bedding housing and the solid storage heap. Nitrogen losses via volatilization as ammonia (NH_3) and N oxides (NO_x) during both phases were modelled using the default mass-flow fractions from the IPCC (2019) guidelines. Comprehensive details regarding the CH_4 and N_2O calculations are provided in Table S2.
Due to the lack of primary sub-metering on the commercial farm, on-farm resource and energy inputs were modeled using representative and geographically coherent literature baselines. Animal water intake, facility cleaning water, and stable electricity consumption were approximated based on the Spanish beef production datasets from Tinitana-Bayas et al. (2024), with electricity sourced from the Spanish national grid. Direct on-farm diesel fuel consumption was estimated following the European conventional beef inventory of Nguyen et al. (2010). To strictly isolate the environmental effects of feed formulation, these resource and energy inputs were kept constant across all evaluated treatments, with all life cycle inventory flows normalized per FU.

Life cycle impact assessment

The LCA was performed using SimaPro v9.3 software to characterize the environmental flows of the compiled inventories. Climate change impact was quantified using the Global Warming Potential over a 100-year time horizon (GWP100) based on the characterization factors from the IPCC (2019) guidelines. Beyond climate change, six other environmental midpoint categories were evaluated using the ReCiPe 2016 midpoint (H) method (V1.04/World, 2010). Dataset was extracted from SimaPro to Excel, where figures for global warming potential relating to CH_4 and N_2O were adjusted to align them with the most recent IPCC methodology (IPCC, 2019).

Table 18. Description of the bull feedlot: input data used for life cycle assessment**.**

	Experimental groups			
Items	Control	Diet A	Diet B	Diet C
Nº of bulls	20	20	19	20
Inputs				
Feed impacts			See Table S1	
Enteric fermentation emissions			See Table S2	
Manure CH_4 and N_2O emissions			See Table S2	
Bedding straw (kg/FU)	0.594	0.594	0.594	0.594
Energy and fuel use				
Electricity (kWh/kg LW gain)	0.099	0.099	0.099	0.099
Diesel (L/kg LW gain)	0.158	0.158	0.158	0.158
Water (L/kg LW gain)	417	417	417	417
Output				
FU	1 kg bull LW gain			
Performance figures				
Bull's growth rate (kg/day)	1.19	1.17	1.04	1.08
Total gain (kg/bull)	176	198	205	208
Dry matter intake (kg/day/bull)	7.93	7.85	7.65	7.42
Study period (days)	165	170	192	177

Statistical Analysis

All statistical analyses were performed in R (R Core Team). Cattle were removed from the feedlot upon reaching a common target slaughter weight/age rather than at a fixed calendar date, so the number of days on feed (DOF) varied among animals and dietary treatments. This was addressed in two complementary ways. First, DOF (rather than calendar date) was used as the time axis for all repeated-measures analyses, so that each animal contributed observations only for the days it was actually present in the feedlot. Second, the time required to reach slaughter weight was itself analyzed as a time-to-event outcome (described below), to formally test whether dietary treatment affected the rate at which cattle reached market weight. Animal performance variables (initial and final BW, total weight gain, and average daily gain, ADG) were analyzed by ANCOVA, with dietary treatment as a fixed effect and DOF and initial BW as covariates, to account for differences in the length of the feeding period and in starting weight among animals. Feed efficiency was expressed as the gain:feed ratio (G:F; total weight gain ÷ total concentrate DM intake over the individual feeding period) and its reciprocal, the feed conversion ratio (FCR), and both were analyzed with the same ANCOVA model. Daily concentrate and water intake were analyzed as repeated measures using linear mixed models, with dietary treatment, DOF, and their interaction as fixed effects and animal as a random intercept. Daily feeder and drinker visit frequency were analyzed with generalized linear mixed models assuming a negative binomial distribution, to account for overdispersion in the count data, with the same fixed- and random-effects structure. Linear models were fitted with the lme4 and lmerTest packages, and count models with glmmTMB. For all models, treatment means were estimated as least-squares (marginal) means using the emmeans package, and pairwise comparisons among dietary treatments were adjusted by the Tukey method; means within a row not sharing a common superscript differ at $P < 0.05$. Time to reaching slaughter weight was analyzed by the Kaplan-Meier method, with differences among dietary treatments assessed by the log-rank test. A Cox proportional hazards model, adjusted for initial BW and initial age, was fitted to estimate the hazard ratio (HR) of reaching slaughter weight for each dietary treatment relative to the control diet. The relationship between feeding behavior (feeder visit frequency) and ADG was examined by Pearson correlation and simple linear regression within each dietary treatment. Significance was declared at $P \leq 0.05$, and $0.05 < P \leq 0.10$ was considered a tendency.

Results and Discussion

Animal performance, feed efficiency, intake, feeding behavior, and time to reaching slaughter weight are summarized in Tables 14 and 15 and Figures 6-12.
Initial and final BW, total weight gain, ADG, and G:F did not differ among dietary treatments (Table 4; $P \geq 0.05$ for all variables). Average daily gain averaged 1.19, 1.17, 1.04, and 1.08 kg/d for Control, Diet A, Diet B, and Diet C, respectively ($P = 0.55$), and G:F averaged 0.20, 0.17, 0.19, and 0.17 kg gain/kg intake ($P = 0.67$). These results indicate that partial or complete replacement of SBM, together with reduced soybean oil and DDGS inclusion, did not compromise growth performance or feed efficiency, supporting the hypothesis that the alternative diets can maintain productivity. Individual animal variation in ADG and G:F is shown in Figures 10 and 11, respectively.

Table 19. Average animal performance throughout the experiment.

Item	Control	Diet A	Diet B	Diet C	SEM	P-value
Initial weight, kg	350	332	326	314	14.0	0.317
Final weight, kg	527	529	531	522	10.5	0.932
Weight gain, kg	196	199	200	191	10.5	0.932
Average daily gain	1.19	1.17	1.04	1.08	0.08	0.552
G:F, kg gain/kg intake	0.20	0.17	0.19	0.17	0.02	0.668

Daily concentrate intake tended to differ among dietary treatments ($P = 0.09$), averaging 6.68, 6.62, 6.45, and 6.02 kg/d for Control, Diet A, Diet B, and Diet C, respectively (Table 5, Figure 1). Feeder visit frequency did not differ among treatments ($P = 0.75$), although the temporal pattern of feeder uses over the feeding period differed among diets (Figure 2). Daily water intake differed among dietary treatments ($P < 0.001$): cattle fed Diet B consumed less water (13.8 L/d) than cattle fed the other three diets (16.9 to 17.8 L/d;), which did not differ from one another (Table 5, Figure 3). This reduction in water intake coincided with the largest reductions in soybean oil and DDGS content in Diet B (Table 1) and may reflect differences in the physicochemical properties or dry matter content of the resulting diet. Drinker visit frequency did not differ among treatments ($P = 0.30$). Across treatments, feeder visit frequency showed a positive association with ADG in Control and Diet B animals, but not in Diet A or Diet C, suggesting that the behavioral drivers of intake and growth may differ depending on diet composition.

Table 20. Average animal concentrate and water intake throughout the experiment.

Item	Control	Diet A	Diet B	Diet C	SEM	P-value
Concentrate intake, kg/d	6.68	6.62	6.45	6.02	0.20	0.09
Feeder visits, n/d	5.93	5.59	5.65	5.97	0.31	0.749
Water intake, kg/d	17.4[a]	17.8[a]	13.8[b]	16.9[a]	0.68	< 0.001
Drinker visits, n/d	6.24	6.77	6.56	7.11	0.33	0.304

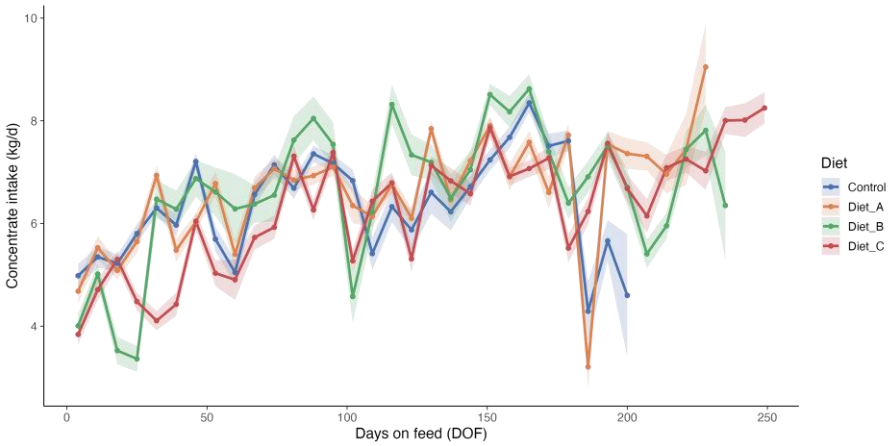


Figure 7. Average concentrate intake throughout the experiment.

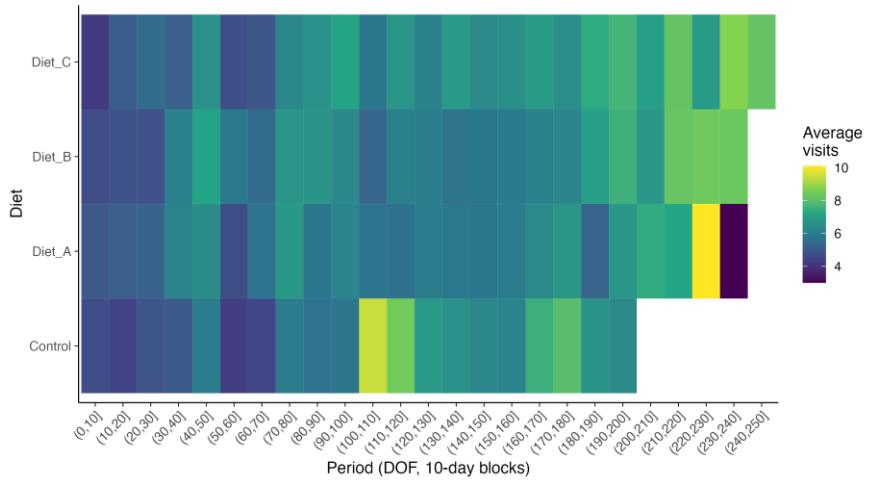


Figure 8. Average visits to the automatic feeders throughout the experiment.

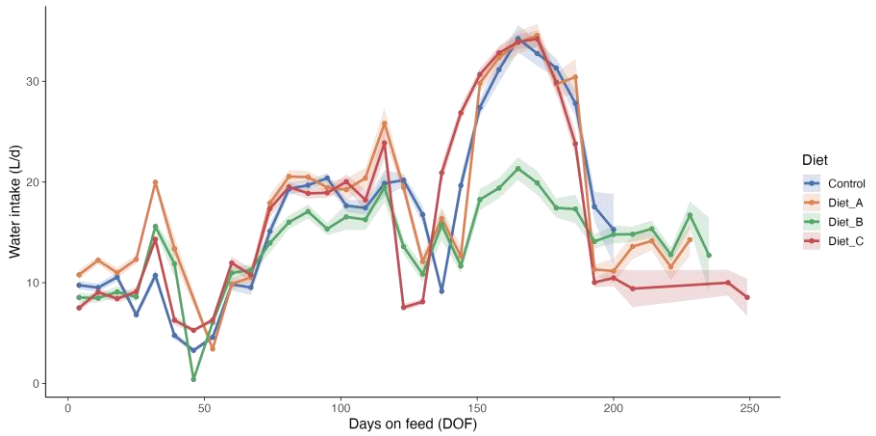


Figure 9. Average water intake throughout the experiment.

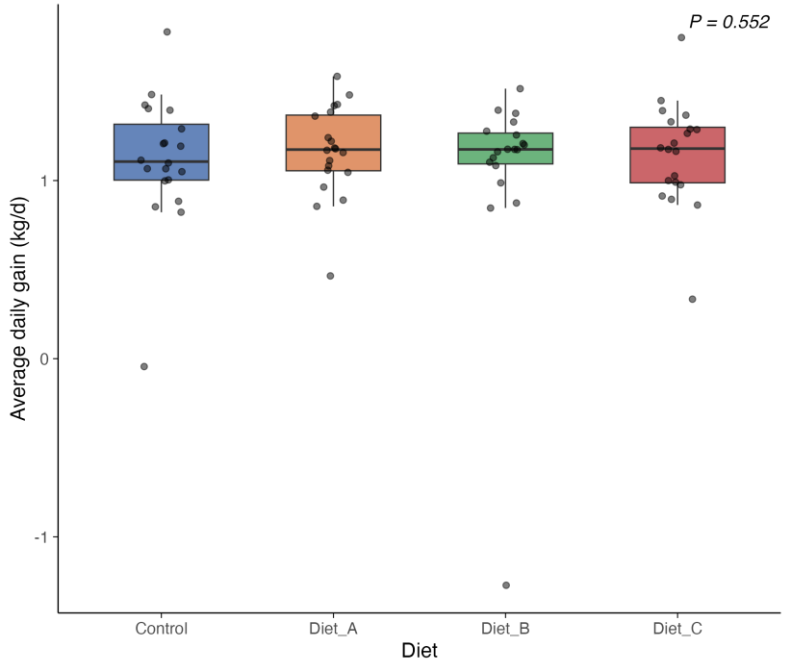


Figure 10. Average daily gain throughout the experiment.

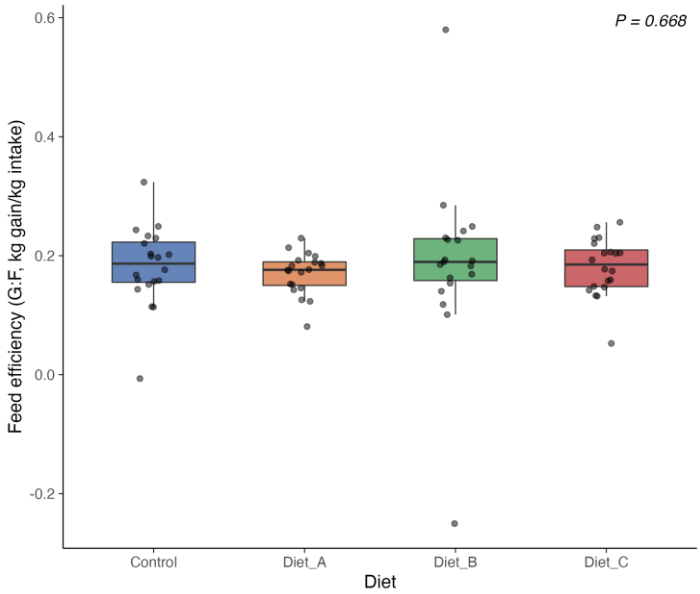


Figure 11. Average feed efficiency throughout the experiment.

Because cattle were removed from the feedlot upon reaching a common target slaughter weight/age rather than at a fixed calendar date, days on feed varied among animals and dietary treatments (Figure 6). Kaplan-Meier analysis showed that the proportion of animals remaining in the feedlot over time differed significantly among dietary treatments (log-rank $P < 0.001$): cattle fed the control diet reached slaughter weight soonest, whereas cattle fed Diet C remained in the feedlot longest. A Cox proportional hazards model adjusted for initial BW and initial age confirmed this pattern: relative to the control diet, the hazard of reaching slaughter weight was 59%, 75%, and 87% lower for Diet A, Diet B, and Diet C, respectively ($P \leq 0.02$ for all), indicating that the alternative, more sustainable diets required a longer feeding period to reach the same target slaughter weight. This is the clearest treatment effect observed in this trial and should be taken into account when interpreting feed efficiency and when estimating the

overall environmental and economic impact of these diets, since a longer time on feed increases total resource use per animal even when daily performance is unaffected.

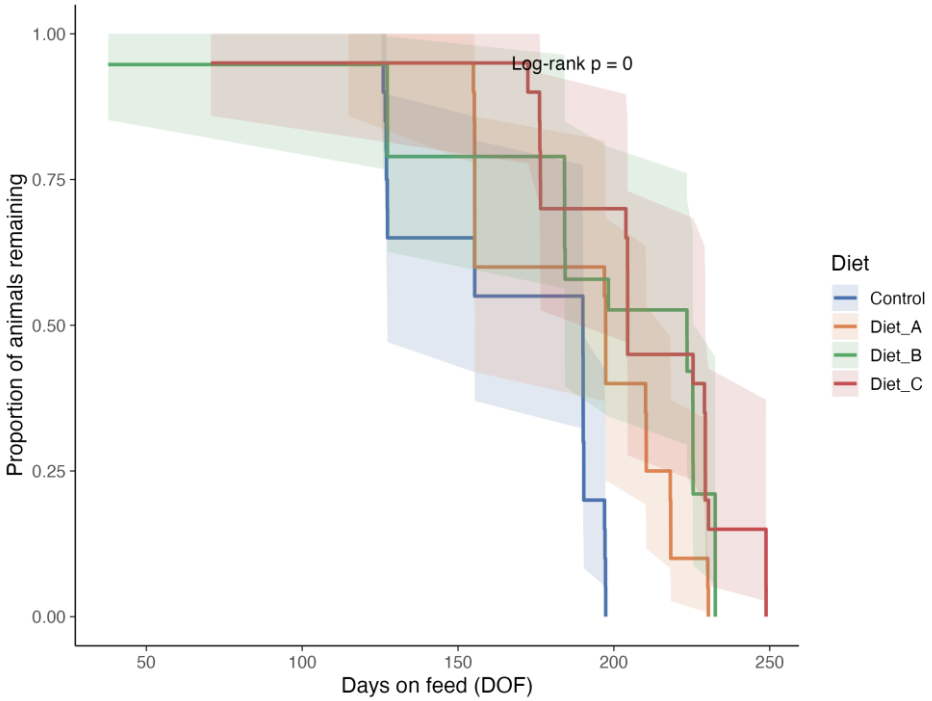


Figure 12. Kaplan-Meier analysis showing the proportion of animals remaining at the farm throughout the experiment.

Life cycle assessment

The comparative potential environmental impacts per kg of LW gain were calculated for the control and experimental diets (Control, Diet A, Diet B, and Diet C) (Fig. 7 a,b,c). Impacts are displayed in percentage terms (%), with the worst-performing scenario for each category scoring 100% and the other treatments showing comparatively proportional scores.

A comparative analysis of the environmental impact categories reveals that the choice of enteric CH_4 predictive model (IPCC, DMI_NDF_, or DMI_EE_C) mainly alters the global warming indicator, leaving the remaining 17 impact categories unchanged across all scenarios. These static categories highlight distinct environmental trade-offs intrinsically linked to the dietary formulations and animal performance. The Control diet results in the greatest impact across several key feed-driven indicators, scoring 100% in land use, water consumption, marine eutrophication, stratospheric ozone depletion, and freshwater ecotoxicity. In particular, its land use impact is approximately 25–30% higher than that of the experimental treatments. These elevated impacts are heavily driven by the dietary formulation; Control is the only diet containing soybean meal (3.48% inclusion) and features the highest total proportion of soy-derived ingredients (oil and hulls). This reliance on conventional soybean products drastically increases the land and water requirements of the diet. Additionally, under the standard IPCC and DMI_NDF_C methodologies, the Control diet also represents the worst-case scenario (100%) for global warming.

When comparing the experimental formulations, Diet B represents the worst-performing scenario across multiple static impact categories, scoring 100% in terrestrial and marine ecotoxicity, fine particulate matter formation, ozone formation (human health), human carcinogenic toxicity, mineral resource scarcity, and terrestrial acidification. These elevated impacts are directly explained by its lower biological performance. Specifically, Diet B recorded the lowest ADG (1.04 kg/day). Because of this reduced daily growth rate, the animals required a longer fattening period, dictating that a larger absolute quantity of feed, electricity, and associated inputs was required per kg of LW gain, while also generating more manure over the animal's lifetime. Notably, when the DMI_EE_C model is applied to calculate enteric

emissions, Diet B's high climate burden is exacerbated, shifting it to become the highest contributor (100%) to global warming as well.
Conversely, while Diet A achieved a higher ADG (1.17 kg/day), it still results in the highest impacts in freshwater eutrophication, fossil resource scarcity, and ionizing radiation. This is likely associated with its specific formulation, particularly the higher reliance on milling by-products (11.9% bran), which carry distinct upstream energy and processing burdens.
Ultimately, Diet C emerges as the most environmentally balanced formulation overall. By successfully removing SBM and relying on a balanced mix of cereals (73.0%), beet pulp (10.6%), and a moderate DDGS inclusion (7.99%), Diet C maintains a moderate ADG (1.08 kg/day) while consistently performing more favourably across the majority of the environmental indicators. It achieves the lowest scores in critical categories such as land use, freshwater eutrophication, fossil resource scarcity, ozone formation (terrestrial ecosystems), marine ecotoxicity, stratospheric ozone depletion, human non-carcinogenic toxicity, freshwater ecotoxicity, and ionizing radiation. Furthermore, it records the lowest global warming impact under both the IPCC and DMI_EE_C models, representing the most robust dietary strategy to mitigate the environmental footprint of the fattening period.

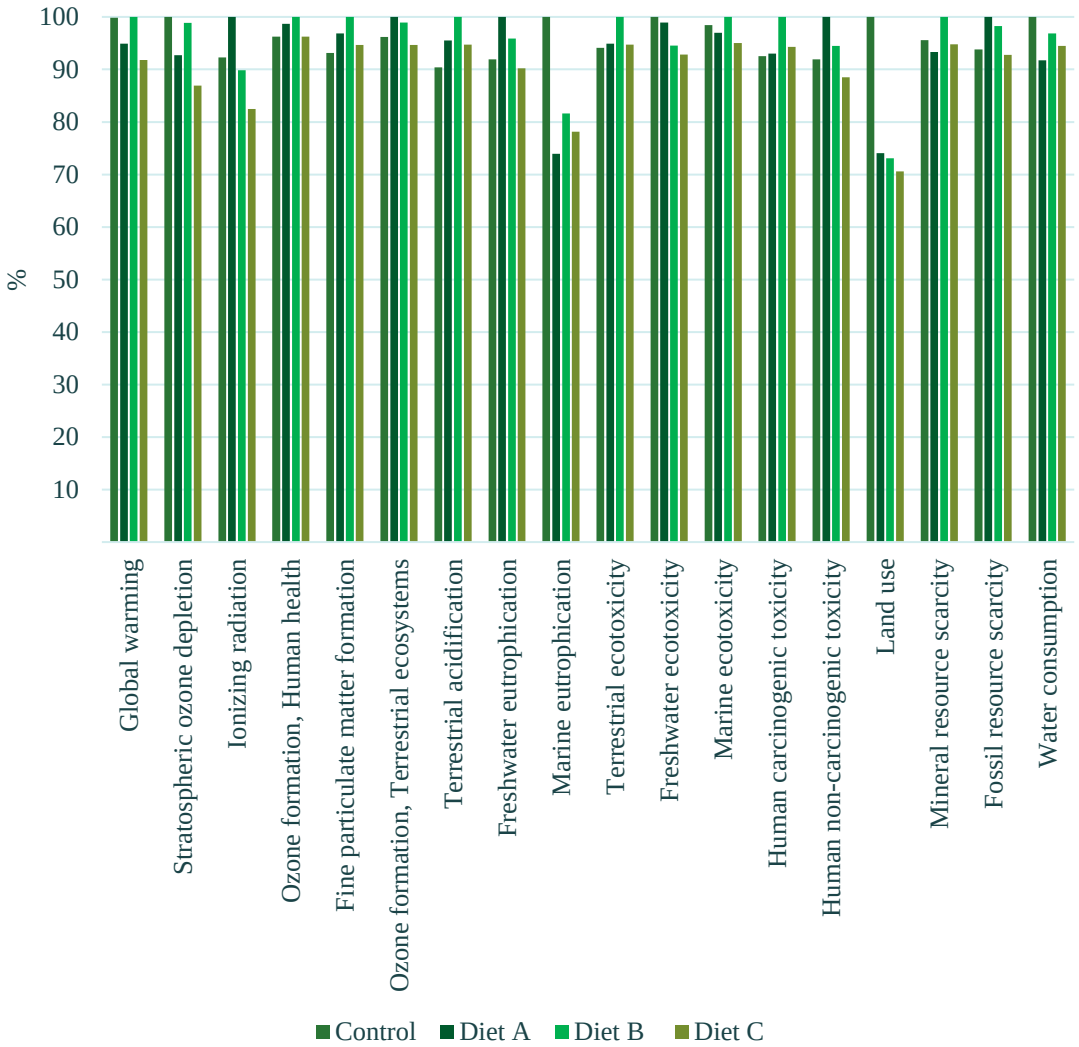


Figure 12a. Comparative potential environmental impacts of the different experimental diets for the different impact categories using IPCC, (2019) for the enteric fermentation.

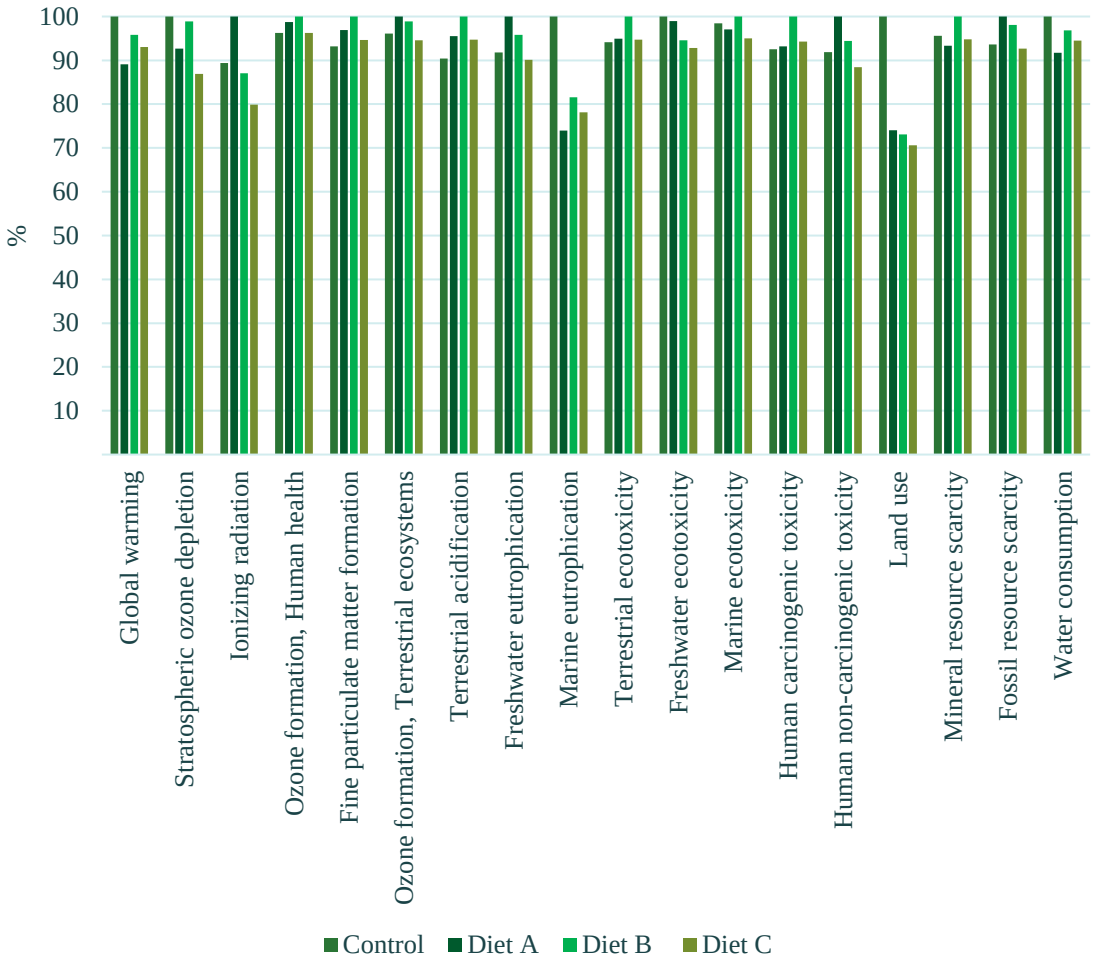


Figure 12b. Comparative potential environmental impacts of the different experimental diets for the different impact categories using the equation DMI_NDF_C from van Lingen et al. (2019) for the enteric fermentation.

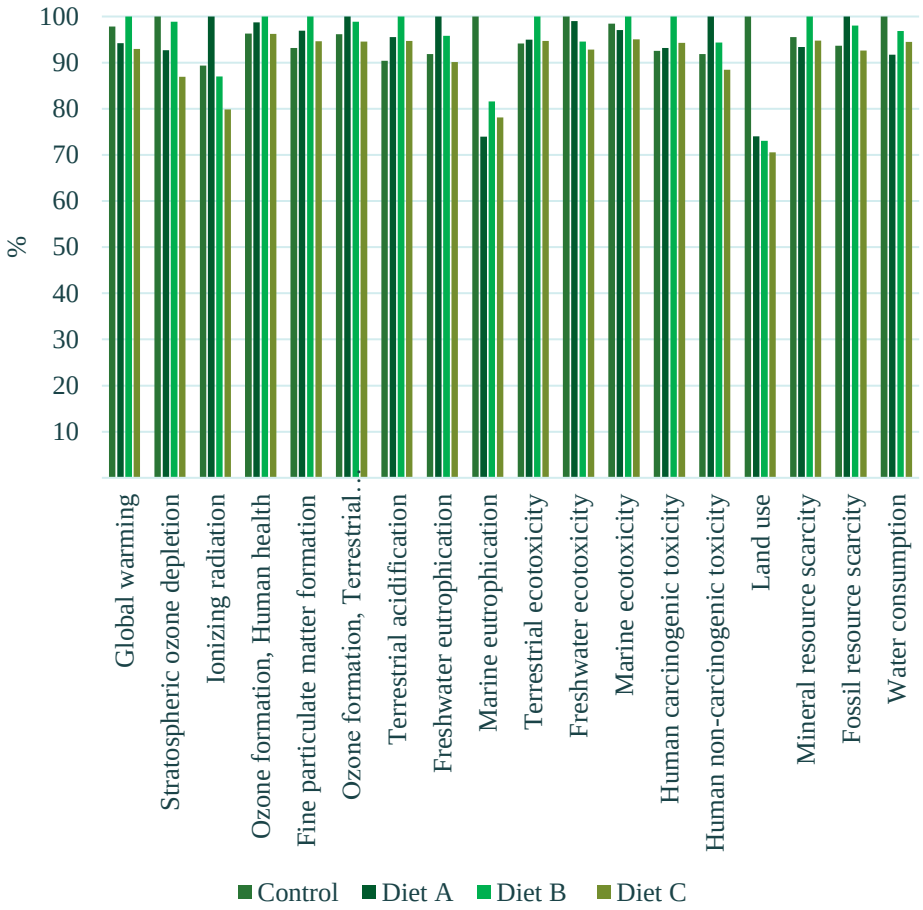


Figure 12c. Comparative potential environmental impacts of the different experimental diets for the different impact categories using the equation DMI_EE_C from van Lingen et al. (2019) for the enteric fermentation.

The sensitivity analysis (Figure 8) revealed that both empirical equations consistently estimated a higher impact in the total Global Warming Potential (GWP100) compared to the IPCC methodology, displaying exclusively positive deviations. However, the magnitude of these variations on the total system's carbon footprint depended directly on the diet formulation and the predictive model used. The DMI_NDF_C based model demonstrated high sensitivity to dietary changes, recording the lowest deviation in Diet A (5.1%) and the highest in Diet C (13.1%). Conversely, the ether extract DMI_EE_C equation exhibited greater predictive stability across all scenarios, remaining within a narrower deviation margin (6.9% to 9.5%). Consequently, while the NDF model estimated the highest total emissions for the Control and C diets, the EE model was more conservative for diets A and B.

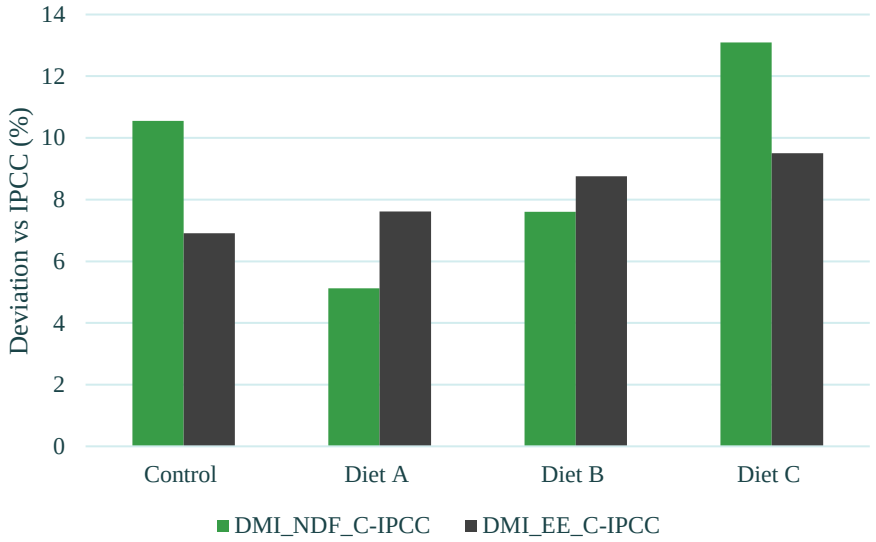


Figure 13. Sensitivity analysis of enteric CH4 emissions: percentage deviation (%) in the total Global Warming Potential (GWP100) calculated using the DMI_NDF_C and DMI_EE_C empirical models from van Lingen et al. (2019) relative to the IPCC, (2019) baseline for the four evaluated diets.

Based on the IPCC (2019) methodology, the breakdown of GHG emissions by source reveals that enteric fermentation and animal feed production are the dominant contributors to the total climate impact across all dietary treatments (Figure 9). The Control diet exhibited the highest overall carbon footprint, primarily driven by a noticeable increase in manure management and animal feed emissions compared to the other groups. Diet B presented a total climate impact comparable to the Control group, but was characterized by generating the highest emissions from enteric fermentation among all treatments. Conversely, Diet C emerged as the most environmentally efficient scenario under this model, recording the lowest total climate impact (below 6.5 kg CO2 eq.). This favourable outcome for Diet C was largely achieved through a visible reduction in the environmental burden associated with the animal feed component and manure management emissions. Furthermore, the enteric fermentation levels for the Control, Diet A, and Diet C were almost identical, indicating that the variations in the total climate impact among these three treatments are dictated almost entirely by manure management and feed composition.
However, evaluating the diets using nutrient-based equations (DMI_NDF_C and DMI_EE_C) from van Lingen et al. (2019), highlights the significant influence of the chosen methodology on the estimated enteric CH_4 emissions and, consequently, the overall carbon footprint. The DMI_EE_C model, based on EE content, yielded the most conservative estimates, driving the total climate impact of all treatments above 7 kg CO_2 eq./FU and positioning Diet B as the least environmentally efficient option overall and the Diet C as the best option which is similar to that found in the IPCC, (2019) methodology. In contrast, the DMI_NDF_C model exhibited the greatest sensitivity to specific dietary composition. Under this fiber-based approach, the environmental ranking shifted remarkably, with Diet A emerging as the most efficient scenario due to a substantial reduction in its estimated enteric emissions. As noted by van Lingen et al. (2019), empirical models for lower-forage diets assign a negative coefficient to NDF because limited dietary variance in the dataset statistically masked the typically positive relationship between fiber and CH_4 production. Since the forage inclusion remained constant across all our treatments, the reduction in estimated emissions for the higher-fiber diets is a direct mathematical artifact of the empirical equation. Given that emissions from manure management, animal feed, and energy use remained constant across all calculations, these findings confirm that fluctuations in the overall environmental performance of the diets are driven exclusively by the predictive mathematical approach used for enteric fermentation. Finally, our findings are in accordance with recent literature related with beef diets; for instance, Davison et al. (2026) reported a highly comparable range of 6.00 to 8.00 kg CO_2 eq. per kg LW gain for intensive fattening cattle system.

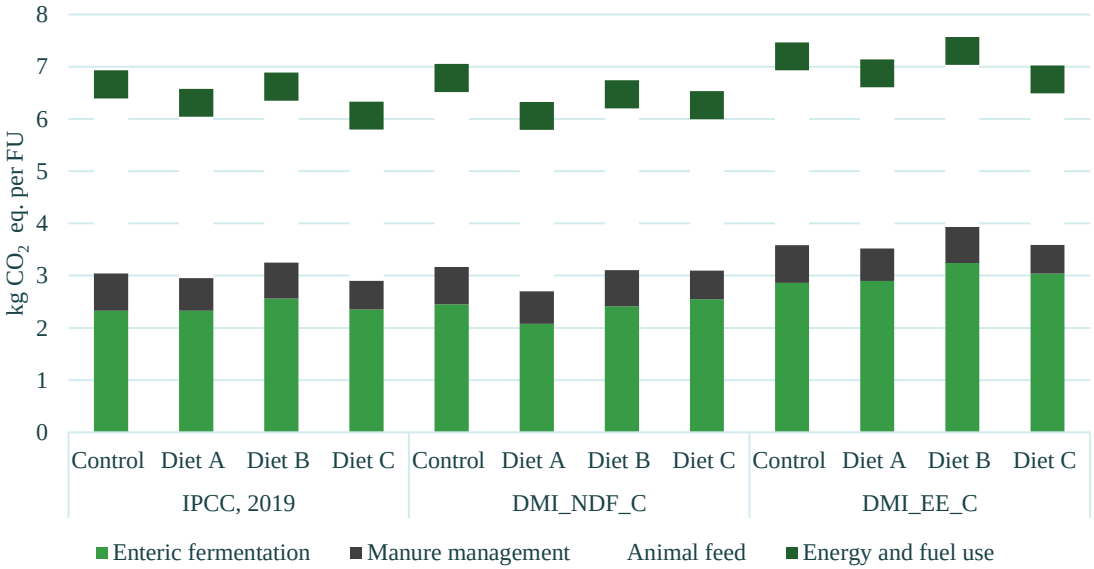


Figure 14. Comparative climate impacts of the different experimental diets by GHG emission sources. The DMI_NDF_C and DMI_EE_C equations for lower-forage diets were taken from van Lingen et al. (2019). FU: functional unit (1 kg liveweight gain).

Specifically, feed-related emissions were 3.35, 3.08, 3.10, and 2.92 kg CO2-eq per FU for CTL, Diet A, Diet B, and Diet C, respectively. When converted to kg CO2-eq per tonne of feed and compared with the diet impact analysis in Deliverable 2.1 (D2.1), we could observe that the trend was similar. However, the differences between Diet B and Diet C in the GFLI-based evaluation are higher than in our study. In our assessment, Diet C exhibited a slightly higher feed-related footprint compared to Diet B. In contrast, the GFLI-based evaluation in D2.1 indicated a notably higher impact for Diet C than for Diet B. We attribute this discrepancy to differences in co-product allocation and Land Use Change (LUC) accounting between the Life Cycle Inventory (LCI) databases used. First, DDGS and wheat bran are co-products of energy-intensive industrial processes (distillation and milling, respectively), and the environmental burden assigned to them varies depending on the allocation approach adopted by each database; this affects how heavily Diet B's higher inclusion of these ingredients is penalized. Second, and more critically, soybean oil is subject to LUC-related emissions associated with imported soy, and the magnitude of this penalty is highly sensitive to how each database applies the standard 20-year deforestation threshold. GFLI appears to assign a comparatively higher LUC burden to soybean oil than Ecoinvent and Agri-footprint, which would explain why Diet C's greater reliance on soybean oil results in a higher footprint under GFLI despite its lower DDGS and wheat bran content. These findings underscore that the relative environmental ranking of alternative beef diets is highly sensitive to LCI database assumptions on co-product allocation and LUC, and should always be interpreted with this limitation in mind.

Conclusions

Replacing SBM and reducing soybean oil and DDGS inclusion, without rumen-protected lysine and methionine supplementation in two of the three alternative diets, did not compromise growth performance, feed efficiency, or overall feeding and drinking behavior of Avileña-Negra Ibérica bulls under commercial feedlot conditions. The main trade-off identified was a longer time required to reach the target slaughter weight with the alternative diets, which should be incorporated into subsequent economic and life cycle assessments of these formulations. Diet B, which combined the largest reductions in soybean oil and DDGS, was also associated with lower water intake.

The LCA reveals that enteric fermentation, manure management, and feed production remain the dominant contributors to the total climate impact of the beef production system. Among the evaluated treatments, replacing SBM with a balanced mix of cereals, beet pulp, and moderate DDGS (Diet C)

emerged as the optimal strategy, minimizing the global warming footprint while avoiding the high land and water use associated with the soy-reliant Control diet. Furthermore, maintaining adequate animal performance is crucial, as reduced growth rates prolong the fattening period and significantly increase overall environmental burdens. Finally, given the absolute dominance of enteric emissions, our sensitivity analysis highlights the importance of carefully selecting predictive models for intensive systems. While nutrient-based empirical equations (such as those using NDF or EE) provide valuable insights, they should be interpreted with caution in lower-forage scenarios, as limited dietary variance may introduce statistical artifacts that obscure the true environmental performance.

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2.2. Environmental and economic impacts of using brewers spent grains for animal feed and anaerobic digestion in the UK (University of Reading)

While previous studies have looked at either the environmental, or economic impacts of utilizing brewers spent grains (BSG) as an animal feed or AD feedstock, to our knowledge, no study to date has compared both the economic and potential environmental impact reduction opportunities for these different utilization pathways, in a UK context. Moreover, when comparing the potential environmental impacts of utilizing BSG as an animal or AD feed, previous research has failed to consider the GHG implications of feed on enteric methane generation. Additionally, recent cost increases in fuel and fertilizer, associated with the conflict in Ukraine, warrant an updated economic assessment to understand implications on the economic performance of the utilization of BSG as an AD and animal feed. To address this knowledge gap, this paper explores the economic and environmental opportunities and risks associated with anaerobically digesting brewer's spent grain (BSG) in the UK. The overall aim is to compare the economic viability and potential environmental impacts of using BSG as a feedstock for AD versus its current primary use as animal feed. The specific objectives of the study are as follows:

- To understand the environmental trade-offs associated with different BSG utilisation pathways.
- To compare the economic implications of the different BSG utilisation pathways.
- To quantify the GHG and land use implications of different BSG utilisation scenarios.
- To outline potential BSG utilisation strategies for the UK.

To achieve the above objectives, we use a combined Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) to determine impacts and identify opportunities for improvement within the agriculture and food sector.

Methodology

The methodology followed in this study has been described in detail in a recent publication (Davison et al., 2026). Figure14 below illustrates the methodological framework followed in the study.

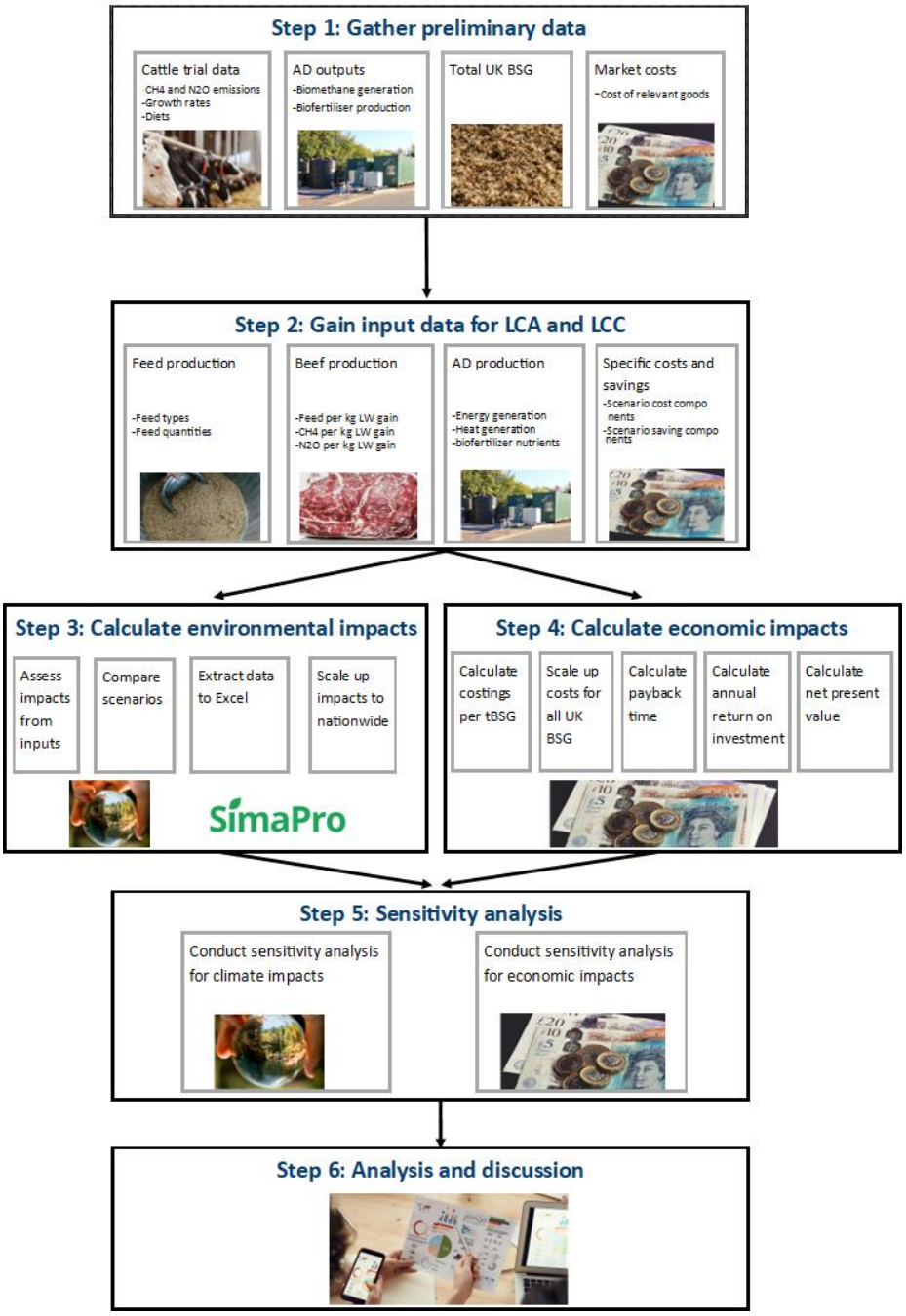


Figure 15. Methodological framework used in this study

Results and discussion

Life Cycle Assessment

Environmental impacts per kg of liveweight gain at sale
The comparative potential environmental impacts per kg of LW gain were calculated for Scenarios 1-3 (Figure 15). Impacts are displayed in percentage terms (%), with the worst performing scenario for each

category scoring 100% and the other scenarios showing comparatively lower scores. S2 results in the greatest impact across eight of the environmental indicators (global warming, land use, water consumption, marine eutrophication, freshwater eutrophication, marine ecotoxicity, freshwater ecotoxicity, and stratospheric ozone depletion). In particular, water consumption is 22% higher than S3, land use is 30% higher than S1, freshwater eutrophication is 49% higher than S3, and freshwater ecotoxicity is 41% higher than S3. These impacts are in part due to the high water requirements and the relatively low yield of soya, as well as the low growth rate associated with the soya diet, leading to higher consumption of other dietary components (besides the high-protein component) per kg of LW gain. When comparing S1 and S3, the potential environmental impacts are more variable. When compared to S1, S3 has lower global warming Impacts (14% lower), water consumption (16% lower) and terrestrial acidification impacts (14% lower) primarily due to having a higher growth rate and less feed consumed per kg LW gain. S3 also has substantially lower impacts on fossil resource scarcity (30% lower), due to AD generating heat and electricity and biofertilizer to substitute fossil-fuels and fossil fuel derived products. Conversely, S1 has substantially lower land use impacts (22% lower) and performs more favourably on other environmental indicators such as human toxicity (almost 100% lower for non-carcinogenic and 7% lower for carcinogenic toxicity), and ozone formation (17% lower for terrestrial and 20% lower for human health impacts) due to utilising a by-product for feed rather than specifically growing field beans as feed (requiring land and polluting Agri-chemicals).

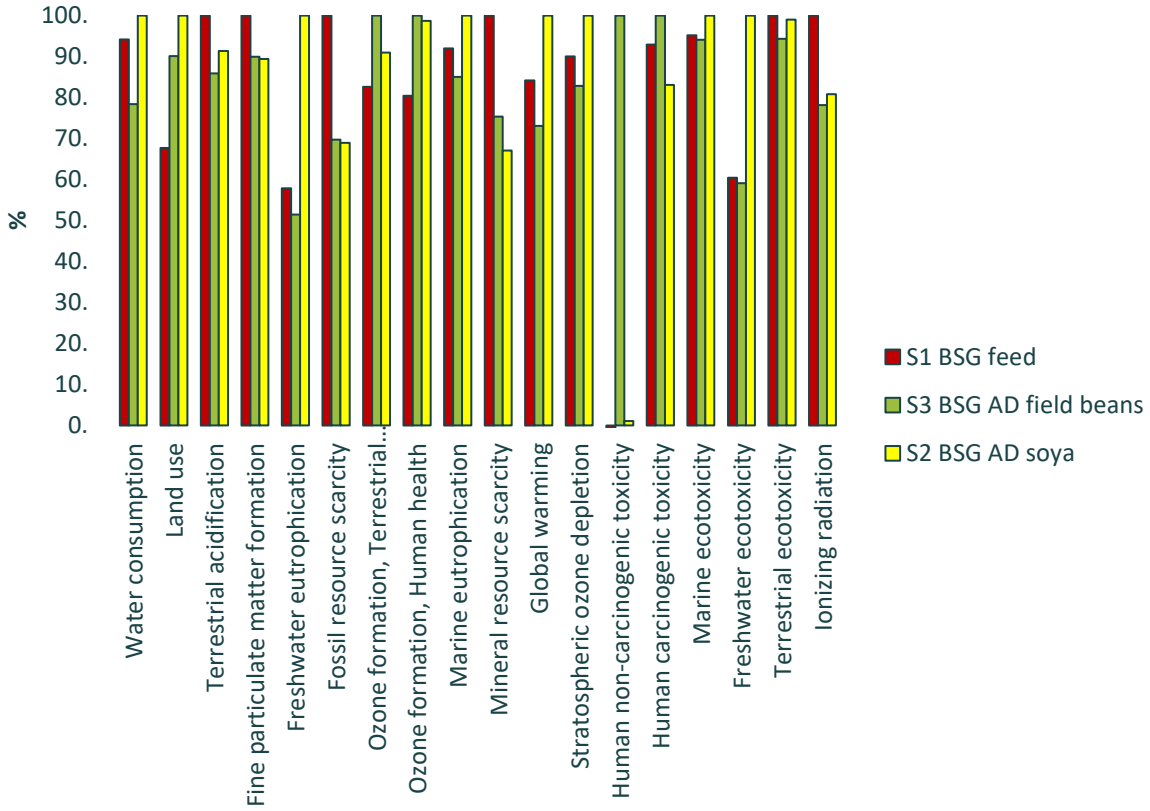


Figure 16. Comparative potential environmental impacts of the different BSG utilisation scenarios for the different impact categories

When looking specifically at GHG impacts (Figure 16), methane and nitrous oxide from enteric fermentation and manure management are the key contributors to GHGs for all scenarios (70% of GHGs for S1, 57% for S2, and 65% for S3), followed by animal feed emissions (21% of GHGs for S1, 40% for S2, and 28% for S3). The soya diet has substantially higher animal feed emissions (118% higher than S1), due to the carbon intense soya component, while the field beans diet has slightly greater feed emissions than BSG (14% higher) due to feed production processes. Conversely, the field beans diet

has the lowest emissions from methane and nitrous oxide (11% lower than S1 and 15% lower than S2), due to the high starch and tannin content in the beans reducing methane from enteric fermentation (increased enteric methane reduction compared to BSG) and this diet providing the greatest growth rate and feed efficiency. Anaerobic digestion of BSG provided a GHG mitigation of around 0.6kgCO2eq per kg of liveweight gain at sale, mainly because of biofertilizer substituting manufactured N and P fertilisers, which offset 8% of GHGs from S2, and 10% of GHGs from S3.

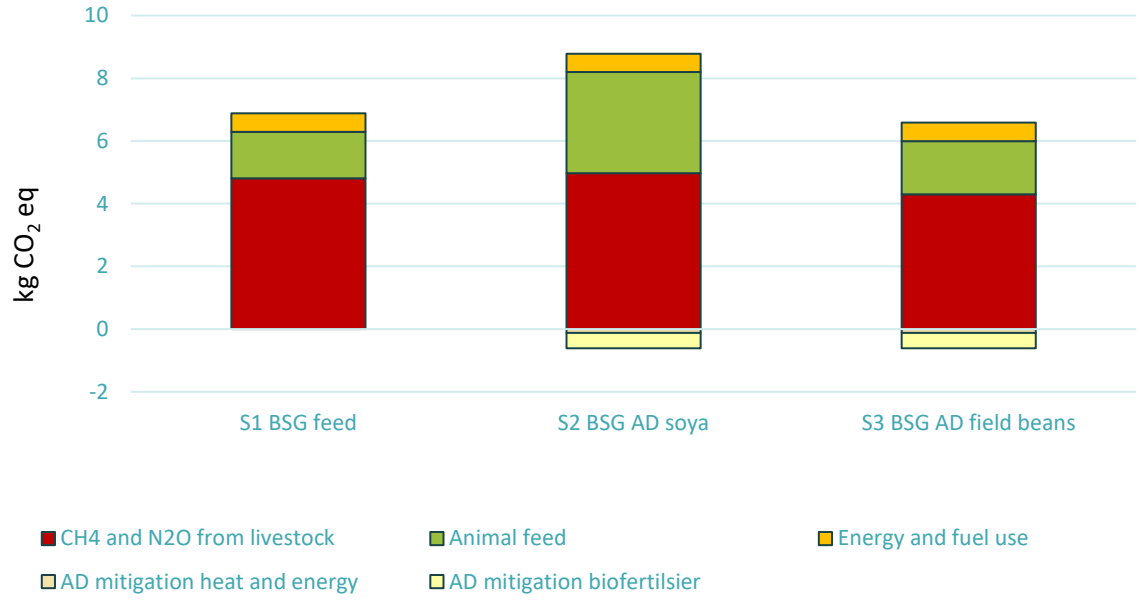


Figure 17. Comparative climate impacts of the different BSG utilisation scenarios by GHG emission sources and mitigations from AD

Scaled up impacts

On the one hand, when compared to S1, S2 resulted in an extra 1.3kgCO2eq per kg LW gain, which increased to 39kt CO2eq if all BSG was used for AD instead of cattle feed to substitute soya (Table 16), due to GHG mitigation from AD being substantially lower than additional GHGs from producing soya. On the other hand, S3 had lower GHGs than the BSG diet (0.9kg kgCO2eq per kg LW gain), as the comparatively lower enteric methane, as well as the GHG mitigation obtained through the AD of BSG, substantially outweighed the reduced feed and enteric methane emissions from S1. Altogether S3 could lead to a sizable GHG saving of 27kt of CO2eq per year when compared to BSG, when scaling up the impacts.

Scenario 2 had considerably greater land use requirements than S1. Altogether, S2 required almost 50 percent more land (m2a crop eq) per kg LW gain, due to substantially more land being required to produce animal feed than the heat, energy and biofertiliser generated through AD. When scaled up, this led to a total extra land requirement of almost 8k hectares when compared to the BSG diet. While S3 had a lower land use requirement than S2 (due to greater cattle growth rates per kg of feed consumed), the land required for this scenario was still substantially greater than for S1. Scenario 3 also required 5.5k hectares more than the S1 would require when scaled up. Land is limited in the UK, with many competing land use requirements (Smith et al., 2019). The extra land requirements could lead to social, economic and potential environmental impacts, including GHGs associated with LUC (Sandrom et al., 2022).

Table 21. Scaled up land use and GHG impacts of BSG scenarios to include utilisation of all BSG in UK

	S1: BSG feed	S2: BSG AD Soya	S3: BSG AD Field beans	**Difference between S2 and S1**	**Difference between S3 and S1**
Net impact per kg liveweight gain					
Net GHGs per kg LW gain ($kgCO_2eq/kg$ LW)	6.88	8.17	5.97	1.3	-0.9
Net land use per liveweight gain (m2a crop eq/kg LW gain)	5.49	8.12	7.32	2.6	1.7
Total annual impact					
Total BSG (Kt/year)	131.7	131.7	131.7	-	-
Total LW gain possible (Kt/year)	29.9	29.9	29.9	-	-
Net GHGs ($KtCO_2eq$/year)	206	244	179	**39**	**-27**
Net land use (Kha)	16.4	24.2	21.9	**7.8**	**5.5**

Potential impact of land use requirements on greenhouse gases

Figure 16 shows the increased or decreased GHGs associated with implementing S2 and S3 using S1 as the reference value if the potential impacts of LUC are considered. If there is no LUC, then the upscaled field beans diet (S3) results in the lowest GHGs; however, if the extra land required came from newly cultivated, non-agricultural land then the field beans diet could have a higher climate impact. If 100% of the extra land came from grassland there would be a marginal increase in the climate impact when compared to the BSG diet (S1). Even if just 25% of the extra land required was derived from forest conversion, then the field beans diet would lead to a marginal increase in climate impact. If 100% of the "new land" came from converted forests, then the field bean diet would go from decreasing GHGs by 27ktCO2eq to increasing GHGs by 120ktCO2eq annually. Deforestation results in substantially greater GHG emissions than grassland conversion because of the greater aboveground carbon stocks being contained in forests (Flynn et al., 2011).

While S2 (BSG AD soya) had a greater climate impact than S1 (BSG feed) before LUC was considered, the climate change risks associated with LUC are clearly much greater than those associated with feed production. If 100% of the extra land requirement came from grassland conversion then the additional GHGs associated with S2 would more than double, from around 39 thousand tonnes of CO2eq to 93 thousand tonnes of CO2eq. Additionally, if 100% of the additional land required came from forest conversion the soya diet would contribute to an annual increase of 250 kt CO2eq when compared to S1. This figure is more than seven times greater than if LUC was not accounted for. It is clear therefore that LUC could play a key role in determining the optimal scenario for GHG mitigation and if extra land use requirements were met by land conversion, LUC impacts would completely overshadow all other GHG considerations.

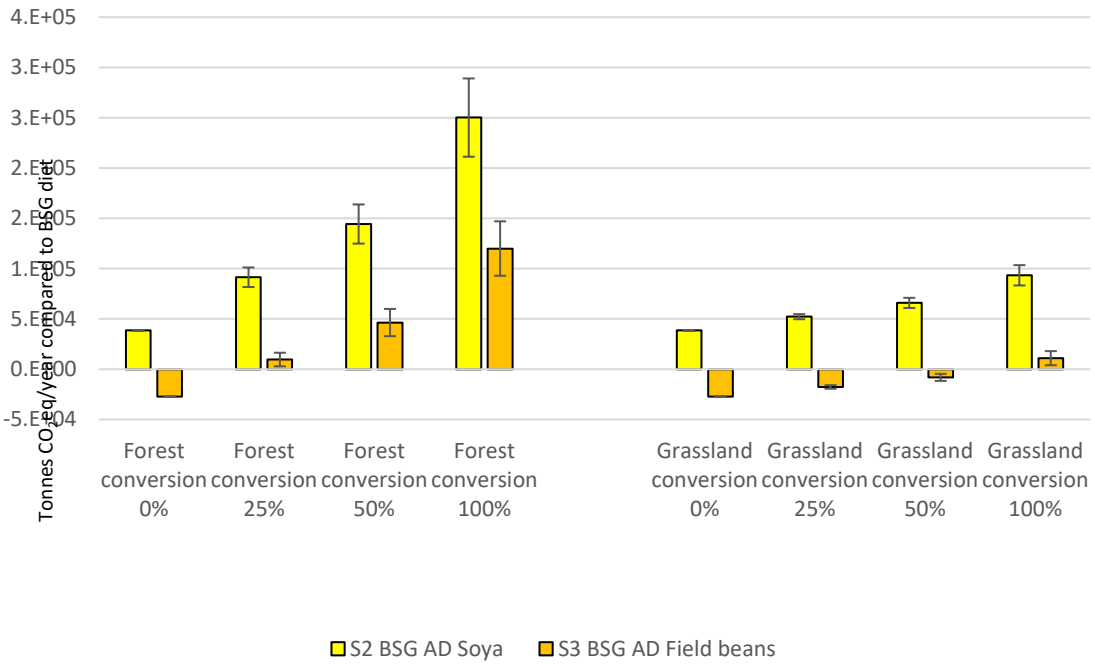


Figure 18. Potential implications of land use on GHGs for soya and field beans diets with error bars for different grassland and forest conversion land use change scenarios

Life Cycle Cost

Life Cycle Cost comparison of animal feed and anaerobic digestion

Scenario 2 and 3 involving AD of BSG were more profitable over their lifecycle than S1 where BSG was sold as cattle feed, although they had a substantially higher initial cost and payback time, as shown in Table 17. If all available BSG in the UK was anaerobically digested, a net gain of over 16 million GBP over the 20-years could be achieved, when compared to selling BSG as an animal feed. This was because AD generated products (especially heat substituting natural gas) were substantially more valuable than BSG was as low-cost animal feed. Nevertheless, if all UK BSG were to be anaerobically digested, substantial initial costs would be required (> £120 million GBP) to purchase sufficient anaerobic digestion equipment. This investment would have a payback time of four years and an annual ROI of 22%. When discounting annual net profit over the lifecycle of the anaerobic digesters, the NPV of the BSG AD scenarios (S2 and S3) was 117 million GBP, 44 million GBP higher than for cattle feed (73 million GBP). Altogether, while the BSG of AD would require a greater investment, a payback time of under 5 years is highly attractive, under current market conditions, and a lifecycle saving of over 300 million GBP could potentially make this a financially sound option for the UK brewing industry, if the current high prices for gas and electricity remain in place and/or increase.

Table 22. Economic implications of using all UK BSG as a cattle feed, or anaerobic digestion feedstock, with the key cost categories and most noteworthy values highlighted in bold.

	S1 BSG cattle feed	**S2 and S3 BSG AD feed**	**S2 and S3 BSG AD feed vs S1 cattle feed**
Capital & installation cost (£ million)	0	123	**123**
Annual costs (£ million)	0	7.8	7.8
Annual savings (£ million)	5.9	36	30
Net annual cost (£ million)	5.9	22.1	**-16.1**
Net Life Cycle Cost (£ million)	**-119**	**-441**	**-323**
Payback time (years)	0	4.3	**4.3**
Return on investment (%)	22.3	N/A	**18.1**
Net present value **(£ million)**	72.8	117.1	44.3

Economic sensitivity analysis

The economic sensitivity analysis found that AD of BSG (S2 and S3) substantially outperformed BSG for animal feed (S1) under all scenarios, with comparative annual net savings not reducing below 5 million GBP (Figure 18). Incorporating the social cost of carbon had the greatest impact on comparative net annual costs. While this made little difference for S3 (BSG AD field beans), it substantially decreased the net annual savings for S2 (AD BSG soya), due to the comparatively high climate impact of the scenario. While the low social cost of carbon scenario had a modest impact, the high social cost of carbon scenario reduced comparative net annual savings of the S2 by almost two-thirds from around 16 million GBP to around 6 million GBP.

The impact of adjusting annual savings from generating heat and energy, as well as selling biofertilizer for the AD scenarios (S2 and S3), or selling cattle feed for the cattle feed scenario (S1) by increasing, or decreasing market values was assessed. These adjustments made a substantial impact to net savings associated with AD of BSG (S2 and S3) compared to the animal feed scenario (S1), due to the comparatively high value of AD products, especially heat substituting natural gas. A 20% increase in the BSG associated revenue would increase net annual savings by 37% from around 16 to 22 million GBP, while a 20% decrease in revenue would lead to a 37% decrease from 16 to 10 million GBP. The market values of fuel, fertiliser and feed have been volatile over the past few years (Mbah and Wasum, 2022) therefore the economics of the scenarios may be sensitive to much greater changes than we have assessed. While changes in the capital and installation cost do not greatly change the net annual savings, they do have a greater impact on payback time, with an increase of 20% pushing the payback time of AD over the desirable 5-year period.

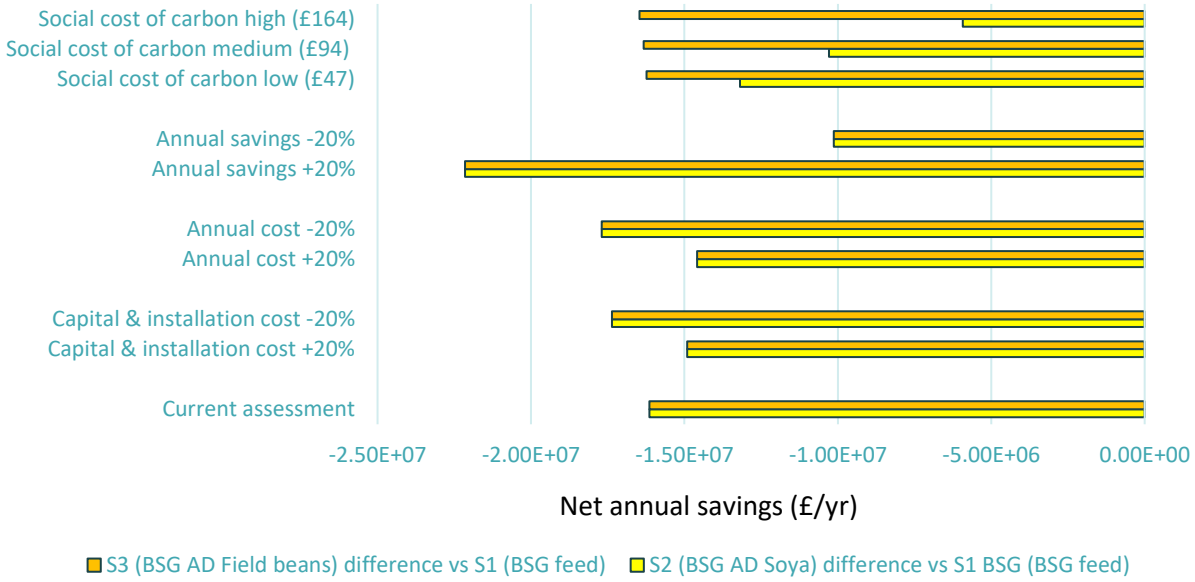


Figure 19. Sensitivity of economic impacts to different potential developments or scenarios involving the implementation of the social cost of carbon, as well as increases and decreases in annual savings, annual costs as well as capital and installation costs

Conclusions

The assessment of the environmental and economic implications of brewer's spent grains utilisation strategies estimated the environmental and economic impacts of using all UK generated brewer's spent grains for anaerobic digestion, or as an animal feed to replace either soya, or field beans. The following impacts were identified:

- It is potentially more environmentally beneficial to utilise brewer's spent grain as an animal feed rather than as an anaerobic digestion feedstock, if the spent grains replace soya. Conversely, if the spent grains are used to replace field beans there are a number of environmental trade-offs across environmental impact categories. The brewer's spent grain diet has much lower land use requirements, but the field beans diet has lower climate change impacts, as well as lower water and fossil resource use.
- The net greenhouse gas and land-use impacts of brewer's spent grain utilisation pathways are highly sensitive to underlying assumptions regarding feed-type substitution: if all of the UK's brewer's spent grain were used for anaerobic digestion, instead of as a soya replacement in cattle feed, the increased demand for soya would result in a large increase in greenhouse gases and increased land requirements (39 Kt CO2eq and 7.8 Kha of land). This effect would be mitigated if the soya demand was instead met by field beans, in this case there would be a large reduction in greenhouse gases, but a substantial additional land requirement (-27ktCO2eq Kt CO2eq and 5.5 Kha of land) following the utilisation of spent grains in anaerobic digestion.
- Utilising brewer's spent grain for anaerobic digestion could result in land use change which would lead to substantial greenhouse gas emissions that could dwarf all other components contributing to greenhouse gas emissions. This would lead the field beans diet to have higher emissions than the brewer's spent grains diet.
- Anaerobic digestion of brewer's spent grain is substantially more profitable than selling the by-product as an animal feed and could provide the UK brewing sector with a net gain of £16 million annually and an annual return of investment of 23%. While it would require a large total initial investment of over £120 million and there may be barriers to smaller breweries investing in small-scale anaerobic

digestion it would have a net present value 44 million GBP higher than selling brewer's spent grains as an animal feed.

If land use change can be avoided, anaerobic digestion of brewer's spent grains combined with the use of field beans in cattle diets could represent a favourable way forward. This is because of the combined economic and climate change mitigation opportunities presented by anaerobic digestion and field bean cultivation. Nevertheless, the current dominant utilisation pathway for most UK brewer's spent grains brings about enormous environmental benefits, especially by reducing the requirement for soya based feed. Using the same material for anaerobic digestion could bring about substantial economic benefits while maintaining a similar environmental effect, although this must be explicitly tempered by the three major caveats revealed in the study: 1) this is highly contingent on avoiding deleterious Land Use Change (LUC), 2) it may not be economically feasible if the cost of the additional land is accounted for, 3) field beans must fully replace brewer's spent grains as the high protein component of cattle feed, as opposed to soya.

Policymakers could take steps to make anaerobic digestion a more viable option for breweries by easing the burden of initial investment, while also supporting broader goals to reduce reliance on soya-based animal feed and protect natural land. Possible policy support measures could include the gradual introduction of taxes or restrictions on imported soya for animal feed to support its eventual phase-out; increased support for advisory services and the provision of interest-free loans to help breweries adopt anaerobic digestion; and planning measures that discourage the conversion of grassland and forests to cropland, helping to limit land use change within the UK.

References

(1) Davison Nicholas, Christos Christodoulou, David Humphries, Kirsty Kliem, Sokratis Stergiadis, Laurence Smith. 2026. Environmental and economic impacts of using brewers spent grains for animal feed and anaerobic digestion. Journal of Cleaner Production, 538,147365, https://doi.org/10.1016/j.jclepro.2025.147365.

3. General Conclusions

1. Local legumes as substitutes for soybean protein in pigs.
The experiments consistently demonstrated that locally produced peas, chickpeas, lentils, faba beans and narrow-leafed lupine can replace a substantial proportion, and in some cases all, of soybean protein in pig diets without compromising overall growth performance. The responses varied according to leume type, genotype and production conditions, with peas generally providing the most consistent nutritional response. The results also indicated potential additional benefits through improved feed efficiency, nitrogen utilisation, carcass characteristics and intestinal health. These findings support locally produced legumes as viable components of more autonomous and resilient European pig-feeding systems.

2. Agri-food by-products in pig diets.
The inclusion of dried berry pomaces illustrates the potential of agri-food co-products to simultaneously valorise nutrient-rich waste streams and maintain animal performance. Blackcurrant and chokeberry pomaces did not adversely affect overall growth or nutrient digestibility and showed potential to improve nitrogen utilisation and reduce gaseous emissions. Their use should nevertheless be based on appropriate selection of the by-product and inclusion level, as nutritional composition and environmental effects can vary substantially among co-products.

3. Low-protein diets in growing-finishing pigs.
Reducing dietary crude protein is an effective strategy for decreasing nitrogen excretion and ammonia emissions while maintaining productive performance and, in some cases, improving feed efficiency and pork quality. The experiments demonstrated that the environmental benefits depend on adequate balancing of essential amino acids. Supplying amino acids to approximately recommended requirements was sufficient to achieve the observed improvements, whereas supplementation above requirements provided no additional benefit. Low-protein feeding therefore represents a practical precision-nutrition strategy for simultaneously improving environmental and production efficiency.

4. Alternative protein sources including insect meal.
Complete replacement of soybean protein by *Hermetia illucens* or *Tenebrio molitor* protein maintained growth performance, nutrient utilisation and intestinal health under the experimental conditions. The particularly favourable performance observed with *Hermetia illucens* supports further evaluation of insect protein as an alternative feed resource. Its wider environmental contribution, however, should be assessed using system-level approaches that account for production substrate, processing and energy requirements.

5. Soybean-free feeding strategies in intensive beef production in Spain.
The Spanish beef study demonstrated the feasibility of formulating soybean-meal-free finishing diets by reducing crude protein content and combining locally produced cereals, sugar beet pulp and alternative protein sources such as DDGS, with rumen-protected amino acids used as a precision-nutrition option. The study provides evidence that reducing dependence on imported soybean products does not necessarily require a single replacement ingredient, but can be achieved through complementary feed resources formulated according to the nutritional requirements of the animal. The integration of automated monitoring and LCA provides an important basis for identifying the most environmentally efficient dietary strategy.

6. Brewers' spent grains and circular feeding strategies in UK beef production.
The UK study highlights the importance of evaluating food-industry co-products within a broader system perspective. Brewers' spent grains can represent a valuable circular feed resource, but their environmental and economic value depends on the alternative uses considered, transport and processing requirements, their effects on animal production and associated enteric methane emissions. Comparing animal feed with alternative utilisation pathways such as anaerobic digestion demonstrates that the sustainability of a co-product cannot be assessed solely from its nutritional value; its opportunity costs and wider environmental and economic consequences must also be considered

Overall conclusion

Taken together, the Re-Livestock experiments demonstrate that reducing the carbon footprint of pig and beef production can be approached through several complementary nutritional strategies rather than through a single feed ingredient. Local protein crops, circular co-products, alternative protein sources and precision low-protein formulation can reduce reliance on imported soybean products while maintaining animal performance. The results also emphasise that environmental performance must be evaluated at the system level: an alternative ingredient is not automatically a lower-carbon option, and its benefits depend on production origin, processing, inclusion level, nutrient utilisation and effects on animal performance and emissions. Future implementation should therefore combine nutritional optimisation with life-cycle and economic assessment to identify solutions that are both environmentally effective and practically viable. Deliverable 2.1. (D4) addresses some of these aspects.

Supplementary material

Table S1. Life cycle inventory of feed ingredients and experimental diets normalized per functional unit.

	Experimental groups							
	Control		Diet A		Diet B		Diet C	
Feed impacts (inputs to SimaPro per FU)								
Barley straw (kg DM/FU)	1.54		1.56		1.76		1.69	
Concentrate feed (kg DM/FU)	5.13		5.15		5.59		5.18	
Feed components	Inclusion (%)	kg/kg LW gain	Inclusion (%)	kg/kg LW gain	Inclusion (%)	kg/kg LW gain	Inclusion (%)	kg/kg LW gain
Barley	43.2	2.21	22.6	1.17	25.2	1.41	26.6	1.38
Beet molasses	2.00	0.100	2.00	0.100	2.00	0.110	2.00	0.100
Beet Pulp (unmolassed)	-	-	4.57	0.240	8.26	0.460	10.6	0.550
Bicalcium phosphate	-	-	-	-	-	-	1.28	0.070
Bran	6.34	0.330	11.9	0.610	3.83	0.210	1.46	0.080
Calcium carbonate	1.51	0.080	1.29	0.070	1.47	0.080	1.56	0.080
Calf premix	0.300	0.020	0.300	0.020	0.300	0.020	0.300	0.020
DDGS	15.0	0.770	8.43	0.430	11.3	0.630	7.99	0.410
Lys, protected	-	-	0.160	0.010	-	-	-	-
Maize	23.4	1.20	45.0	2.32	45.0	2.52	45.0	2.33
Met, protected	-	-	0.160	0.010	-	-	-	-
Salt	0.300	0.020	0.300	0.020	0.400	0.020	0.400	0.020
Soybean hull	1.39	0.070	0.450	0.020	-	-	-	-
SBM 47%, (USA)	3.48	0.180	-	-	-	-	-	-
Soybean oil (USA)	2.62	0.130	2.34	0.120	1.72	0.100	2.30	0.120
Sodium bicarbonate	0.500	0.030	1.29	0.030	0.500	0.030	0.500	0.030

Control: commercial control diet, including imported soybean meal (SBM) and soybean oil. Diets A, B and C excluded SBM and relied on cereals and beet pulp to replace the removed protein and energy. Diet A: 11.5% reduction in soybean oil and 44.0% reduction in DDGS relative to Control, with rumen-protected Lys and Met. Diet B: 34.6% reduction in soybean oil and 24.7% reduction in DDGS relative to Control, without amino acid supplementation. Diet C: 11.5% reduction in soybean oil and 47.3% reduction in DDGS relative to Control, without amino acid supplementation. FU: functional unit. LW: live weight. Forage to concentrate ratio in each diet was 20:80.

Table S2. Formulas and parameters used for estimating methane (CH_4) and nitrous oxide (N_2O) emissions from enteric fermentation and manure management

	Experimental groups			
	Control	Diet A	Diet B	Diet C
Bull's emissions (CH_4 and N_2O)				
Enteric fermentation calculations				
IPCC (2019; kg CH_4 $head^{-1}$ yr^{-1})			$EF = \frac{GEI \times (Ym / 100) \times 365}{55.65}$	
Bulls's CH_4 emissions	36.1	35.6	34.8	33.1
Bulls's emissions (kg $head^{-1}$ day^{-1})	0.099	0.097	0.095	0.090
van Lingen et al. (2019) equations				
DMI_NDF_C (kg CH_4 $head^{-1}$ day^{-1})	0.104	0.087	0.090	0.098
DMI_EE_C (kg CH_4 $head^{-1}$ day^{-1})	0.122	0.121	0.120	0.117
Manure CH_4 and N_2O calculations (IPCC, 2019)				
CH_4 emissions equation	Daily volatile solids × no. of days [CH_4 producing capacity×0.67× (methane conversion factor ÷ 100)]			
CH_4 (kgCH_4 $head^{-1}$ day^{-1})	0.00128	0.00131	0.00135	0.00106
N_2O equation	Direct N_2O + indirect N_2O (N_2O from volatilisation + N_2O from leaching)			
N_2O (kg day^{-1})	0.00300	0.00254	0.00249	0.00207
Total CH_4 (kg CH_4 day^{-1})	Total CH_4 manure + daily CH_4 enteric fermentation			
CH_4 and N_2O emissions per FU	Total CH_4 ÷ daily LW gain; N_2O ÷ daily LW gain			

Control: commercial control diet, including imported soybean meal (SBM) and soybean oil. Diets A, B and C excluded SBM and relied on cereals and beet pulp to replace the removed protein and energy. Diet A: 11.5% reduction in soybean oil and 44.0% reduction in DDGS relative to Control, with rumen-protected Lys and Met. Diet B: 34.6% reduction in soybean oil and 24.7% reduction in DDGS relative to Control, without amino acid supplementation. Diet C: 11.5% reduction in soybean oil and 47.3% reduction in DDGS relative to Control, without amino acid supplementation. GEI: gross energy intake (MJ/day). *Ym*: CH_4 conversion factor set at 4.00%. The DMI_NDF_C and DMI_EE_C equations for lower-forage diets were taken from van Lingen et al. (2019). FU: functional unit. LW: liveweight.